

Final Report

Project AQ02

Source attribution and critical loads assessment for
Special Areas of Conservation and Special Protection Areas in the UK

February/2007

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Dissemination status

Unrestricted

Project funders

Fiona Mactaggart, Scotland and Northern Ireland Forum for Environmental Research
Colin Gillespie, Scottish Environment Protection Agency
David Bell, Environment and Heritage Service
Colin Powlesland, Environment Agency

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Research contractor

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Key words: Air pollution, Nitrogen deposition, Acid deposition, Critical Loads, Natura 2000, Atmospheric modeling.

PART I:
SITE RELEVANT CRITICAL LOADS

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EXECUTIVE SUMMARY

1. To assess the impact of industrial emissions on European Sites (SAC and SPA), a methodology was developed for allocating site relevant critical loads of acidity and nutrient nitrogen to designated features.
2. Three systems of habitat classification, EUNIS, Annex I of the Habitats Directive, and BAP, were used in the linking of designated features to empirical critical loads of nitrogen and critical loads of acidity.
3. The process of allocating critical loads was divided into two phases relating to the use of two different methodologies. SAC Annex I habitats and Annex II plant species were treated together in one methodology, while SPA and SAC Annex II non-plant species were treated with a separate methodology.
4. Designated features for SACs and SPAs, were assessed for their sensitivity to acidification and eutrophication and suitable critical loads were then allocated for each. The assessment of sensitivity and linkages to critical load habitat classes were carried out by habitat and species specialists from English Nature, CEH, JNCC and Scottish Natural Heritage.
5. Critical loads for SPA features and SAC Annex II 'non-plant' features were assigned based on known linkages between the species and the habitat on which it depends either for breeding, feeding or roosting.
6. Six broad habitats for acidity were used in the assignment of critical loads of acidity (acid grassland, calcareous grassland, dwarf shrub heath, bog, montane, unmanaged coniferous and broadleaved woodland). Critical loads of acidity for these habitat classes were mapped for the whole of the UK at a resolution of 1 km.
7. Components of the critical load function, CL_{maxS}, CL_{minN}, and CL_{maxN}, were produced for all six habitats. By overlaying the 1 km critical loads data onto the polygons of the sites, maximum and minimum values for each polygon for each acidity habitat class were obtained. .
8. Critical loads for nitrogen were based on the Berne empirical critical loads defined at the Berne workshop. Impacts of exceedance and reliability of a critical load were described.
9. Critical Loads for acidity for freshwater features were assessed using the results of previous work reported by Curtis *et al.*, 2003 (Freshwater Screening and Assessment Based on Freshwater Critical Loads).
10. A database in Excel was produced to provide a lookup table for each for SAC, SPA to obtain lists of features and relevant critical load values. Written guidance was drafted to allow users to interpret their sites of interest. The Excel database was later transferred to the APIS web site at www.apis.ac.uk/query_sitebased.html.
11. A limitation of this assessment is the assumption that all European interest features are present in every polygon. Using the dominant soil type for producing acidity critical loads can be inaccurate for habitats not found on this dominant soil type. Furthermore, some features are found on more than one soil type, leading to the requirement to assess some features at a site specific level.
12. The present assessment does not address the integration between air pollution and other factors like land-use management and climate change in respect of exceedances of critical loads. However, combined with an assessment of air pollution conducted in parallel in this project (Dore et al 2005), the results provide the basis for a suitable screening approach for assessing the impacts of air pollution on sensitive sites and features around the UK.

1 BACKGROUND

As a requirement for implementation of the Habitats Directive in the UK, it is necessary to conduct a country-wide assessment of the extent to which Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) may be under threat by existing and future emissions of air pollution from major point and area sources. The Habitats Directive was incorporated into law in the UK by means of the Conservation (Natural Habitats & c.) Regulations 1994 (known as the Habitats Regulations). Under Regulation 50 of the Habitat Regulations, existing consents given to industry must be reviewed by competent bodies, and the obligations of the Habitats Directive must be endorsed. For any consents which are likely to have a significant effect on a European site (e.g. SAC or SPA), either individually or in combination with others, an appropriate assessment of the implications for the site should be carried out. Subject to the certain provisions (Regulation 49) the competent authority shall only issue the consent after having ascertained that it will not adversely affect the integrity of a European site.

Not only do the Regulations require a “review of consents” for existing permits, but any new permits are subject to the provisions of Regulations 48 and 49. These further regulations have implications for UK conservation and pollution agencies when carrying out duties under Pollution Prevention Control and the Integrated Pollution Prevention and Control (IPPC) Directive.

Potentially, industrial processes may exert a range of different types of impact on European Sites. The combustion of fossil fuels, in particular, may release large quantities of sulphur and oxidised nitrogen, which can then be deposited on European sites leading to acidification and eutrophication. However, deposition of sulphur and nitrogen may also arise as a result of releases from other sources such as transport, domestic or commercial activities, the long-range transport of sulphur and oxidised nitrogen, or more locally as a result of ammonia released from agricultural activities. There is therefore a requirement to assess the relative contribution of these different sources to sulphur and nitrogen deposition before deciding what, where or if remedial action may need to be taken to control releases from these activities.

The present report describes part of the work of a project designed to provide datasets to inform the assessment of the contribution of industrial sources and their impacts on European Sites. There are two main tasks in this project: assignment of site relevant critical loads and estimation of the source attribution of pollutant deposition. These are described in turn below.

1.1 Site-relevant critical loads

In the first part of the project, work has been conducted to assign critical loads values for European sites and for the interest features (habitats, plant and animal species) occurring on those sites.

Critical loads can be defined as “a quantitative estimate of an exposure to one or more pollutants below which harmful effects on specified sensitive elements of the environment do not occur, according to present knowledge” (Nilsson and Grennfelt 1988, UBA 1993). They can be seen as the degree of tolerance of an ecosystem to deposition of air pollutants over time, and can be used to protect a number of different receptors within an ecosystem including habitats, individual species or soil.

The definition of site-relevant critical loads, or more strictly feature-relevant critical loads, represents the allocation of the most relevant critical load for every designated feature at a particular European site. Under this project, critical loads for both acidity and nutrient nitrogen are assigned for each designated feature that is sensitive to acidification or

eutrophication. Levels of justification are given for allocating a particular critical load class and information is provided about the critical load values and impacts of an exceedance of this critical load. Other information is given about a suitable Biodiversity Action Plan (BAP) Broad Habitat type for each feature and notes describe feature ecology or habitat preferences (e.g. bird species).

Since the present assessment focuses on individual European sites, it is necessary to assign critical loads to each of the site according to local conditions. It should be noted that straightforward use of the UK mapped critical loads values is not sufficient for this purpose: firstly, critical loads are not mapped for all locations in the UK (e.g. no mapping below threshold values of appropriate land cover types); secondly, the national mapping does not take full account of the details of the individual SACs and SPAs, such as the actual habitats and species that are designated as interest features for statutory protection. The present report describes the approaches applied to generate critical loads for each of the interest features of these European sites, with in particular emphasis on one of the key challenges of when and how to assign critical loads values for plant and animal species.

1.2 Source apportionment

In the second part of the project, an atmospheric transport and deposition model was used to quantify deposition “foot-prints” of the major industrial point sources of SO₂ and NO_x, and of the other main pollution sectors (e.g. transport and agriculture, including from ammonia). These deposition footprints are combined so that it becomes possible to attribute quantitatively the sources of the deposition received by each European designated site (SAC/SPA). The long-range dispersion model FRAME (Fine Resolution Multi-pollutant Exchange) was used to estimate the pollution footprint for each source, providing a mechanism for defining the percentage contributions of individual sources to each 5 km grid square.

Combined together, the source attribution and critical loads assessment provide key inputs needed for screening sensitive sites and features throughout the UK. Such a screening assessment can be used to identify the main European sites and interest features that are under significant threat of air pollution. This will allow resources to be used more effectively, by focusing subsequent detailed assessment on the sites of key concern. While Task 1 is reviewed in this report, Task 2, describing the FRAME modelling and source attribution work, is documented in the report Source Attribution (Dore *et al.*, 2005).

2 INTRODUCTION - SITE RELEVANT CRITICAL LOADS

2.1 European Sites and designated features

The Habitats Directive, and the Habitat regulations in the UK, provides a framework for designating and protecting Special Areas of Conservation (SACs) for habitats and Special Protection Areas (SPAs) for birds across the UK. sites have gained designation status across the UK. Annexes (I and II) to the Directive list 189 habitats and 788 species. Of these there are around 76 Annex I habitat types in the UK, of which 22 are priority habitat types. Of the Annex II species, 43 are native to, and normally resident in, the UK, of which one is a priority species (JNCC 2000). For SPAs there are over 100 individual bird species listed under the Birds Directive (Council Directive 79/409/EEC) for the UK, which have subsequently been subsumed in to the Habitats Directive. Many are categorised as breeding, migratory or wintering birds, qualifying them as a separate feature. For example, *Anas strepera* (breeding) and *Anas strepera* (non-breeding) are listed as two separate species accounts.

Of particular importance in carrying out this task was the methodology behind integrating three different habitat classification schemes:

- Annex I habitats: as cited in the Habitats Directive;
- EUNIS (European Nature Information System) habitats: now used in the harmonising of habitat classification and naming conventions;
- BAP (Biodiversity Action Plan) Broad Habitats: Used in this case for the purposes of mapping critical load habitats.

There is a need for linkages between an Annex I habitat and empirical nitrogen critical load habitats based on EUNIS. Critical loads for acidity are based on BAP Broad Habitats, and, as a result, linkages must be made between the Annex I habitats and BAP Broad Habitats. SPA designated features (bird species) must first be linked to a suitable BAP Broad Habitat and then to EUNIS for empirical critical loads of nitrogen and to critical loads Broad Habitats for acidity.

There have been a number of attempts to match all these different classifications. Davies & Moss (2002) linked EUNIS habitats with Annex I habitats, while the UK National Focus Centre (NFC) (Hall et al., 2003) has linked BAP Broad Habitats with EUNIS for nutrient nitrogen, with acidity critical load Broad Habitats linked to EUNIS classes. A comparison of habitats classifications is published in the NBN habitats dictionary (<http://www.nbn.org.uk/habitats/index.htm> 06/10/05). In the present project we have made every effort to use these linkages in our methodology, but matches between classes are never exact and there is still a recognised level of expert judgement needed in matching a best fit. This expert judgement has come from a number of habitat experts at English Nature, CEH, Scottish Natural Heritage and the JNCC. In order to show the levels of certainty in assigning critical loads to designated features, and matching Annex I, Annex II and SPA features to EUNIS and/or Broad Habitats (which are used by UNECE and the NFC respectively), we have used four levels of justification. These are worded specifically depending on whether the feature is a habitat or species feature, but the four levels can be summarised below as:

- Level 1: Equivalent or same habitat name as the EUNIS/NFC habitat.
- Level 2: Most similar habitat is represented by the EUNIS/NFC habitat.
- Level 3: Based on expert judgement
- Level 4: No comparable habitat.

2.2 Critical Loads for Nutrient Nitrogen

Empirical critical loads for nitrogen deposition on semi-natural ecosystems were last reviewed under the UNECE at the Bern Workshop (11-13 November 2002). At this workshop, empirical nitrogen critical loads, based on observed changes in the structure and function of ecosystems, field addition experiments, mesocosm studies, and in some cases dynamic ecosystem modelling, were evaluated for specific receptor groups of natural and semi-natural ecosystems (UNECE 2003). Critical load values were agreed as a range of deposition values due to intra-ecosystem variation between different regions, finite intervals between nitrogen addition experiments, and potential uncertainties in estimated atmospheric deposition values. The unit of deposition is $\text{kg N ha}^{-1} \text{ yr}^{-1}$. To support the uncertainty or certainty of a critical load value, levels of reliability have been recommended in the UNECE report, and these have been utilised in the site relevant critical loads database. There are three levels of uncertainty:

- Reliable: when a number of published papers of various studies showed comparable results

- Quite reliable: when results of some studies were comparable
- Expert judgement: when no empirical data were available and the critical load is based on expert judgement, which were likely to be comparable to this ecosystem.

Impacts of exceedance of the critical load for each ecosystem type described in the UNECE report have also been transposed into the site relevant critical loads database. Likely impacts of exceedance can include changes in plant species composition, direct effects of toxicity to vegetation, soil acidification, and increased susceptibility to secondary stress (e.g. drought).

2.3 Critical Loads for Acidity

Critical loads for acidity are based on soil type, including weathering processes and rainfall pH. Soil acidification is essentially the loss of buffering capacity in soils leading to a decrease in pH. Acidification can either be caused by a loss of exchangeable base cations or an increase in the negative charges without further additions of base cations (NEG-TAP 2001). Deposition of sulphur, as sulphate (SO_4^{2-}), and nitrogen, as nitrate (NO_3^-), ammonium (NH_4^+) and nitric acid (HNO_3), can cause acidification and both sulphur and nitrogen compounds must be taken into account when assessing acidification of soils.

Empirical critical loads for soils are applied to areas of non-woodland terrestrial habitats, and these critical loads are set to protect the soils upon which the habitats depend. These soils have been divided into five soil classes on the basis of the dominant weatherable minerals (ICP 2004). This contrasts with the mass balance acidity critical loads, which is applied for woodland habitats critical loads; this aims to protect both the soils and the vegetation (Hall et al. 2003). For the purposes of determining links between critical loads and atmospheric emissions of sulphur and nitrogen, critical loads are further derived to produce a maximum critical load for sulphur (CLmax), a minimum critical load for nitrogen (CLminN) and a maximum critical load for nitrogen (CLmaxN). These components define the critical load function and when compared with deposition data for sulphur and nitrogen, they can be used to assess critical load exceedances. A representation of the critical load function graph (Figure 1), showing an exceedance of the critical load, provides a very useful tool for assessing any potential remedial action required to meet or better the critical load (i.e. whether S or N deposition or both need to be reduced to avoid exceedance of the critical load). In general, but not always the most practicable method, is to reduce both pollutants by the smallest amount, represented by the shortest distance (z). The unit of deposition is $\text{keq}(\text{H}^+) \text{ha}^{-1} \text{yr}^{-1}$.

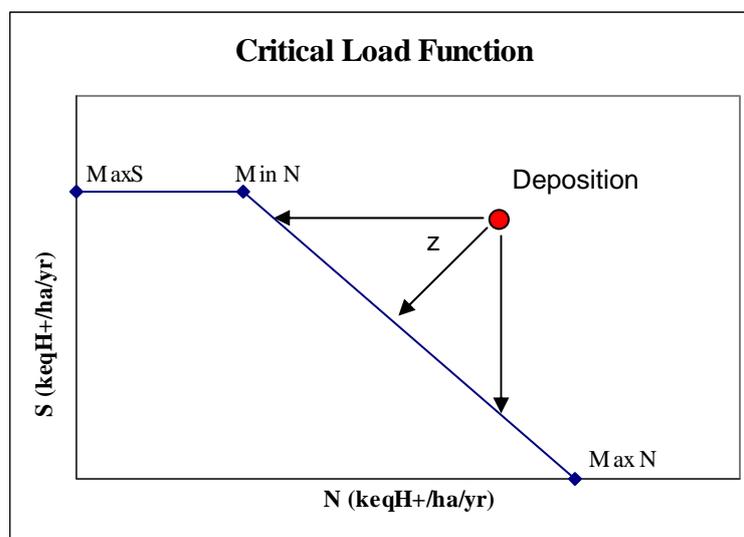


Figure 1 - Critical Load Function in relation to deposition of nitrogen and sulphur. Z represents the smallest reduction of both pollutants to reach the critical load

Impacts of acidification on vegetation include the loss of species typical of intermediate pH in favour of acid-resistance or acid-loving species. Leaching of base cations will cause a decrease in soil base saturation, increasing the mobilisation and availability of Al^{3+} ions, causing toxicity to plants and mycorrhiza, and lower plants, for example, bryophytes and lichens. Soil acidification can also have impacts for bird species whereby calcium-rich prey species can become scarce through acidification (Graveland et al., 1994; Green 1998).

3 METHODOLOGY**3.1 Assigning Relevant Critical Loads to designated features**

Assigning the most relevant critical load to the designated features was split into 2 phases:

1. Assessment of Annex I habitat features and Annex II plant species features. Annex II features have been combined because plant species are seen as being in situ and therefore are part of the habitat, rather than other Annex II species, which are mobile.
2. Assessment of SPA bird features and Annex II non-plant species features

The second phase, concerning the assessment of Annex II non-plant features, used the same method as the SPA features, and is described in the Section 3.15.

3.1.1 Assigning critical loads for acidity

There are eight habitat classifications for acidity (acid grassland, calcareous grassland, dwarf shrub heath, bog, montane, unmanaged coniferous and broadleaved woodland, managed deciduous woodland, and managed coniferous woodland), all based on BAP Broad Habitats as described in the UK Biodiversity Action Plan (1994). Only six of these were used in this assessment, which excluded managed coniferous and managed deciduous woodlands, since these are not protected within the network European designated sites. Although it could be argued that woodland conservation sites are managed, the management focus is primarily to protect ground-flora species or the trees themselves, which is distinct from the priorities and practices of commercial woodland management.

The next step was to assess whether the designated feature is sensitive to acidification. This assessment was conducted using the expert judgement of a series of specialists from English Nature, SNH and CEH. For the majority of features, acidification can potentially have an impact where deposition is high enough and/or where the soil has low buffering capacities. Only features that were coastal, especially those residing below the tide mark (e.g. estuaries, reefs or coastal lagoons) were not sensitive to acidification due to the buffering capacity from the high levels of base cations in sea salt. Certain calcareous features, for example limestone pavements and alkaline fens, were also classed as not being sensitive to acidification due to their high buffering capacity. Once the sensitivity of each feature has been established, the Annex 1 habitat and Annex II plant features were matched to their corresponding critical load Broad Habitat.

The justification level (Section 2.1) was noted for the transparency of the judgement and a description of the impacts of exceedance was also provided.

3.1.2 Freshwater critical loads

Freshwater critical loads of acidity were also considered in the site relevant critical loads assessment. Critical loads for freshwaters, are based on steady state models and water chemistry, are set against a target organism, *Salmo trutta* (Brown trout). The acid neutralising capacity (ANC $\mu\text{eq l}^{-1}$) of the water is used as an indicator of the viability of the target organism, with this set at a critical value of $0 \mu\text{eq l}^{-1}$, which matches to a 50% probability of reduced trout populations occurring (Curtis et al. 2003).

The results of Curtis et al. (2003) have been used in the assessment of freshwater critical loads here. In their report, Curtis et al. identified designated features associated with freshwaters and have also produced a list of potentially acid sensitive freshwater SAC and SPA sites where these features are found. This was carried out in three stages: 1) identifying designated features associated with freshwater habitats, 2) identifying the potentially sensitive features in terms of habitat sensitivity, and 3) a refinement of the risk assessment. A final shortlist of 32 SACs and 1 SPA were identified as being potentially sensitive together with sensitive features.

3.1.3 Assigning critical loads for nutrient nitrogen

A similar process was adopted to that described in Section 3.1.1 to assign critical loads for nutrient nitrogen. Judgement on the sensitivities of designated features to eutrophication effects were carried out. Only a minority of habitats were assessed as not sensitive to eutrophication effects from atmospheric sources (e.g. estuaries, reefs or coastal lagoons). Annex I habitat and Annex II plant species were linked with the most suitable EUNIS class used in classifying empirical critical load habitat classes. Similar justifications for this match were noted for transparency and consistency. Using the critical loads defined at the Bern Workshop (UNECE 2003), the relevant critical load values, reliability of these values and the likely impacts of exceedance were all noted.

3.1.4 Exceptions

There were a couple of exceptions when allocating empirical critical loads for nitrogen. Three Annex I habitat features did not match a suitable EUNIS class for which a critical load for nitrogen is assigned (Inland salt meadows, Vegetated sea cliffs of the Atlantic and Baltic coasts, and Dunes with *Hippophae rhamnoides*). In addition, it was not possible to match one Annex II species (*Marsupella profunda*) to a suitable critical load class. For these features a further investigation of the current available science may provide a more suitable estimate and a sensible critical load could be acquired. For the purposes of this assessment no critical load was allocated for these features and any assessment will be made on a site by site basis.

Empirical critical loads for freshwater features are limited to oligotrophic inland surface waters, where a range of field and experimental evidence is available (Bobbink et al., 1996). Since most surface waters (especially non-oligotrophic waters) in the UK are limited by phosphorous, nitrogen enrichment is considered unimportant. Nitrogen limitation does, however, appear to be significant in many coastal standing waters and is now accepted as being more widespread in freshwaters than previously thought, although generally as a consequence of elevated phosphorus concentrations (Moss et al. 1997). There is also growing evidence of temporally dynamic co-limitation by nitrogen and phosphorus in standing waters (Hessen et al., 1997c; Maberly et al., 2003). Consideration for these freshwater features can only be taken at a site specific level where N/P limitation is better understood. Guidance was given within the site relevant database to assess these features at the site level.

3.1.5 Assigning critical loads for SPA features and Annex II non-plant species.

There are few, if any, instances of direct effects on bird species from nitrogen and acid deposition. Therefore, assigning critical loads directly to bird features is an unsuitable method for assessing likely impacts. However, by examining the relation between a bird's integrity and that of its habitat provides for a better causal link between potential bird decline and atmospheric pollutant deposition. An indication of potential impacts can thus be determined by considering whether the established impacts of critical load exceedance on a habitat are likely to affect the suitability for bird breeding, feeding or roosting. The same methodology was applied for Annex II non-plant species. Such expert judgments were based on the generic conservation objectives of each species provided by English Nature, and further Quality Control assessments were carried out by other experts at the conservation agencies and CEH. Where the habitat in which a bird or non-plant species occurs was assessed to be insensitive to either acidity or eutrophication, no critical load was assigned.

For each species the following series of questions were applied:

1. What is the relevant BAP Broad Habitat for this species? For example, in the case of bird species - what is the habitat that the SPA bird species is dependent upon in terms of breeding, feeding or roosting? This often led to a bird species being dependant on more than one BAP broad habitat, and each instance was recognised as a new record.
2. Is this habitat sensitive to eutrophication (from atmospheric deposition) or acidification?
Similar judgements were applied as in section 3.1.1 and 3.1.3.
3. If yes, what are the impacts of eutrophication or acidification on this habitat and will it affect the viability of the breeding, feeding or sometime roosting of that species? Judgements were made by qualified experts using the best available science. Sometimes there are positive impacts of eutrophication in the case of enhanced food supply. It is recognized that there is uncertainty in judging whether eutrophication will have a positive effect on a bird species (i.e. enhanced food supply) or whether it the nitrogen supply would be in detrimental excess (i.e. algal blooms or suppression of an essential part of the soil fauna). This very much depends on the state of the habitat. However, where evident both positive and negative effects have been indicated.
4. If there are potential negative effects on the species, the most relevant critical loads for nutrient nitrogen or critical load for acidity is assigned based on the broad habitat in which the species is present.
5. Similar justifications were made as that for SAC features and the relevant critical load values and impacts were noted.

The decision flow diagram in Figure 2 shows an example of how the links between habitat impacts and the consequent bird feature impacts were assessed. The example describes the assignment of a critical load for nutrient nitrogen to the feature *Charadrius morinellus* (Dotterel).

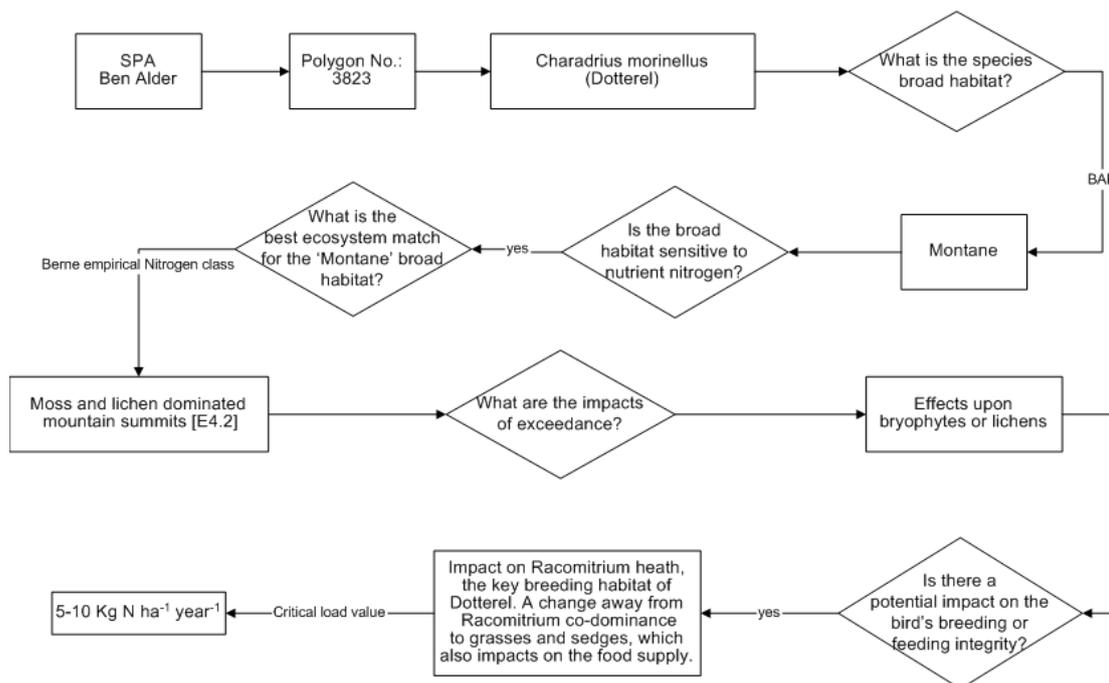


Figure 2: Decision flow diagram for assessing potential impact on SPA features.

3.2 SAC and SPA site data

The database system was built up by using a combination of ArcView GIS, Microsoft Access and Excel. GIS shape files of all European sites (SAC and SPA) were supplied by the JNCC and these were used together with the generation of critical loads of acidity (see section 3.2.1 below), and the site relevant critical loads, to provide a complete record for each designated feature at each site. Unlike critical loads of acidity, which are primarily based on soil type, and hence dependent on soil maps, empirical critical loads of nutrient nitrogen are habitat based and values are static for the whole of the UK. Therefore, no further mapping was required for critical loads of nutrient nitrogen.

3.2.1 Generating Critical Loads of acidity

Dataset of acidity critical loads with a 1 km grid resolution were generated for six habitat classes (acid grassland, calcareous grassland, dwarf shrub heath, bog, montane, and, unmanaged coniferous and broadleaved woodland), assuming the habitat is present in every 1 km grid square of the UK for which input data to the critical load calculations are available (for example, soils data are not available for some urban/water areas of the country). By assuming each habitat can be found in every 1 km, a bottom up approach is adopted whereby the local knowledge of conservation officers is used in the application of the results as to whether certain habitat features occur within individual European Sites. In effect, by assuming a habitat can be in every grid square in the UK, all eventualities are covered especially where a site contains a small area of a particular habitat, or small mosaics of habitat. The methods used to generate these critical loads data-sets were consistent with those used for the February 2003 data submission to the Coordination Centre for Effects for work under the UNECE Convention on Long-Range Transboundary Air Pollution. Full details of these methods are provided in the UK National Focal Centre February 2003 Status Report available from <http://critloads.ceh.ac.uk>.

Critical loads for acidity were produced for the 3 elements of the critical load function namely:

- Maximum critical load of sulphur (CLmaxS)
- Minimum critical load of nitrogen (CLminN)
- Maximum critical load of nitrogen (CLmaxN)

Each of these will be provided in respect of calculations for acid grassland, calcareous grassland, dwarf shrub heath, bog, montane, and, unmanaged coniferous and broadleaved woodland.

3.2.2 Assigning acidity critical loads to site polygons

Each SAC and SPA site is made up of a number of GIS polygons or for smaller sites often just one polygon. Using ArcView GiS, the 1 km acidity critical loads for each of the six habitat classes, were placed over the site polygons to produce a grid of critical load values. For example, six 1 km grid squares (or parts of) might overlay a particular polygon area. By comparing the critical load values across each of the six 1 km grid squares, the maximum and minimum values for each polygon, and for each of the six broad habitat types, were determined. These maximum and minimum values make up the CLmaxS, CLminN and CLmaxN components that comprise the critical load function. Output data from this exercise for each of the six habitat classes were thus:

- maximumCLmaxS,
- maximumCLminN
- maximumCLmaxN
- minimumCLmaxS,
- minimumCLminN
- minimumCLmaxN

Where only one km grid square fitted into the polygon, the maximum and minimum values were, by definition, the same.

4 RESULTS & DISCUSSION

4.1 Building the database

By combining site information, including feature lists and polygon IDs, and the critical loads work, a database of site based critical loads was built for each SAC and SPA in the UK network. Some further filtering was carried out for SSSIs for England and Wales and some calcareous features (see section 4.2).

The finished database was presented as an interactive Excel spreadsheet database. Here the user can navigate to a list of features for every polygon at each site by a system of drop-down menus. A full list of all the features associated with this polygon and site was presented together with the critical loads values for nutrient nitrogen and acidity. An additional add-on was designed whereby a user could select a designated feature and plot the critical load function of acidity (similar to Figure 1). A full list of categories (columns) and brief notes on each can be found in Appendix 1 and Appendix 2 for SACs and SPAs, respectively.

4.2 Further filtering

Given that the derivation of critical loads of acidity are based on the most dominant soil type in a 1km square, an incorrect allocation of the critical load to a designated feature may occur. For example, where a 'calcareous' feature is found on a small area of calcareous soil in an otherwise acid area, the critical load for the dominant soil type is very low reflecting the dominant acid soil. Where a calcareous feature occurs on an otherwise

non-calcareous dominant soil area, it has been largely possible to identify these issues and assign the appropriate critical load in the database. This has been done by artificially raising the empirical critical load for acidity to the top non-peat soil class of 4.0 keq ha⁻¹ yr⁻¹. This filtering has occurred for the following features which are principally found on calcareous soil: Alpine and subalpine calcareous grasslands; Semi-natural dry grasslands and scrubland facies: on calcareous substrates (*Festuco-Brometalia*) and the same feature for (important orchid sites); Calaminarian grasslands of the *Violetalia calaminariae*; Calcareous rocky slopes with chasmophytic vegetation; and species *Gentianella anglica* and *Vertigo angustior*. Of course, similar inconsistencies can occur the other way round, in that a small area of acid grassland, for example, could be found in a grid square with a predominantly calcareous soil. However, while the empirical critical load for calcareous soils is always assigned the top soil class (equal to 4.0 keq ha⁻¹ yr⁻¹), the remaining five habitat classes can occur in any of the soil classifications. Due to this, filtering out these anomalies was not carried out and users have been directed to guidance notes (see section 4.3) where ‘suspicious’ critical load values occur.

One of the main limitations in carrying out this exercise has been the obstacle of not knowing the spatial distribution of designated features at a designated site. This has necessitated the assumption that all features are present in every polygon of given SAC or SPA. Recent work carried by English Nature has started to map where the European features lie within the associated SSSI. Given that SACs are mainly made up of groups of selected SSSIs, and that polygons have often been mapped to match the SSSI boundaries in this piece of work, it was possible to use the SSSI associations in English SACs to filter out features that are not found in a particular polygon. This helped in streamlining the database and avoiding unnecessary duplication of data.

Finally, freshwater features, and their associated SACs and SPAs, were filtered for sensitivity to acidification from according the assessment of Curtis *et al.* (2003) as described in section 3.1.2. A full list of the 32 SAC and 1 SPA is provided in Table 1 below. Only these sites and features were listed as sensitive to acidification and appropriate ANC values are given in the database.

Table 1 - List of acid sensitive Natura 2000 sites (from Curtis *et al.* 2003)

SAC Code	SAC Name
UK0012557	The New Forest
UK0030075	Afon Eden
UK0030046	Afon Gwyrfaï a Llyn Cwellyn
UK0012670	Afon Teifi/ River Teifi
UK0013010	Afon Tywi/ River Tywi
UK0030100	Brown Moss
UK0014789	Coedydd Derw a Safleoedd Ystlumod Meirion/ Meirionnydd Oakwoods and Bat Sites
UK0014790	Cors Caron
UK0012929	Dartmoor
UK0019857	Dorset Heaths
UK0030038	Dorset Heaths (Purbeck and Wareham) and Studland Dunes
UK0012602	East Devon Pebblebed Heaths
UK0012928	Elenydd
UK0012946	Eryri/ Snowdonia
UK0030148	Exmoor and Quantock Oakwoods
UK0012685	Gower Commons/ Tiroedd Comin Gwyr
UK0030144	Gweunydd Blaencleddau

UK0012960	Lake District High Fells
UK0030205	Migneint a Dduallt
UK0030229	North West Pembrokeshire Commons/ Comins Gogledd Orllewin Sir Benfor
UK0012970	Oak Mere
UK0012598	Preseli
UK0012945	Rhinog
UK0030056	River Camel
UK0030032	River Derwent and Bassenthwaite Lake
UK0012643	River Eden
UK0030057	River Ehen
UK0030256	River Kent
UK0012691	River Tweed
UK0012642	River Wye/ Afon Gwy
UK0013045	St David`s/ Ty Ddewi
UK0013577	The Broads
SPA Code	SPA Name
UK9009141	Abberton Reservoir

4.3 Guidance

Some notes have been added to the Excel spreadsheet that provides guidance and instruction in the use of critical loads and the critical load function. Bullet points of known inconsistencies and problems are outlined together with ways of solving such inconsistencies and inaccuracies. Average critical loads for acidity for the UK are provided to show an expected critical load, thereby allowing the user to develop a feel for what is happening, or should be happening, at their site. In addition, these UK averages are plotted as critical load function graphs, providing a visual representation of the likelihood of a critical load being within the bounds of reality. For example, a Natura 2000 montane feature has been allocated CLmaxS and CLmaxN values of around 4 keq ha⁻¹ yr⁻¹ in the database. Compared to the UK means of these parameters these values appear to be too high and a lower value would be more appropriate. Comparing the critical load values of other polygons, for the same feature, within the same site may also reveal more expected values.

4.4 Limitations in using critical loads

The application of critical loads to site based assessments should, in general, be based on the soil type and location on which the feature lies. Using national data sets in this exercise has led to a number of inconsistencies and limitations in the use of critical loads to assess site based habitat and species features.

1. Adopting the use of national critical loads for acidity gives rise to a number of problems including:
 - National maps for critical loads of acidity are based on the dominant soil type for each 1 km grid square. This leads to problems for all features that make up small areas or mosaics of habitats, but are not represented by the dominant soil type for that 1 km grid square.
 - Some features can be found on a number of different soil types, (e.g. ranging from calcareous to acidic and is therefore represented by a number of different acidity classes. For example *Juniper communis* occurs on calcareous, acidic and montane soils. The critical load values will in most cases reflect the correct underlying soil type, but prior knowledge of the soil type on which the feature occurs on a particular site should also be taken into account.

- Some features, which are sensitive to acidity, may have missing critical load values. This occurs particularly with coastal sites where the 1 km gridded national critical loads maps from which the site relevant values have been derived do not exactly match the real coastline. In these cases an indication of the likely values can be obtained from other polygons within the same site.
- 2. For all sites there is the assumption that all features are in every polygon. Future improvements in the mapping of designated features to SSSI or polygon level (as has been initiated for SACs in England) would greatly improve the efficiency of the database and avoid duplication of feature accounts.
- 3. The use of critical loads in assessing the importance of exceedance, and how this is relative to other drivers of ecological change impacting on the features like land management or climate change, is not tackled in this project. Integrating such drivers was never intended for the purposes of this exercise, which focuses on conducting a screening of likely sensitive feature and sites. Such drivers would certainly apply to decisions made when a more detailed site based assessment is conducted. For example, many of the eutrophication effects need to consider the active land management context of grazing or mowing.
- 4. In the case of bird species this assessment does not take into account the ability for birds to select optimal locations, or the dependence for additional foraging habitats during critical parts of the year. This is particularly important for agricultural habitats which need to be in the vicinity for many of the listed species. An example, like the above, will have consequences for the process of selecting future areas, currently outside the SPA network, that are suitable for protecting a bird's integrity.

4.5 Application of the database

The current excel database was converted to the APIS (Air Pollution Information System) website: www.apis.ac.uk/query_sitebased.html. Users can search by SAC or SPA and retrieve information on the sensitivities of each designated feature to acid and nitrogen deposition, including critical load values and a breakdown of contributions to deposition from national sources. Figure 3 shows an example result page for a selected feature at a SAC. The results page includes the feature description, the sensitivities, the nutrient nitrogen and acidity critical loads, the critical load function for acidity, the total deposition and pie charts showing the source attribution. Users can choose between years 2003 or 2010 to see the changes to the deposition based on the different emissions for each year. Users can also select the top 10 sources and plot them on the critical load function graph.



Home | by Pollutant | by Habitat | by Issue | by Location | Biomonitoring | Glossary | Comments

SAC > Hill of Towanreef > Blanket bogs

Interest Feature: Blanket bogs

EUNIS Code: D1.2 ⓘ

Interest Layname: Blanket bog

Priority Habitat: N

Ecological Notes: n/a

Sensitive to Nitrogen: Y

Sensitive to Acidity: Y

UNECE (2003) Nitrogen class: Raised and blanket bogs ⓘ

EUNIS Code: D1

Ecosystem Impacts: Change in species composition, N saturation of Sphagnum.

Uncertainty: reliable

Empirical Critical Loads: 5-10 Kg N/ha/yr

Acidity Class: Bogs ⓘ

Ecosystem Impacts: Leaching will cause a decrease in soil base saturation, increasing the availability of Al³⁺ ions, mobilisation of Al³⁺ may cause toxicity to plants and mycorrhiza, may have direct effect on lower plants (bryophytes and lichens).

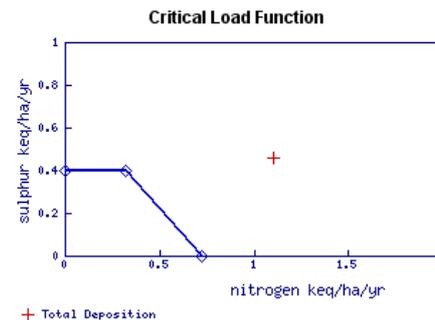
MaxCLmaxN: 0.72 **MaxCLmaxS:** 0.40 **MaxCLminN:** 0.32

MinCLmaxN: 0.62 **MinCLmaxS:** 0.30 **MinCLminN:** 0.32

Year: 2003

N Deposition: 0.84 keq/ha/yr

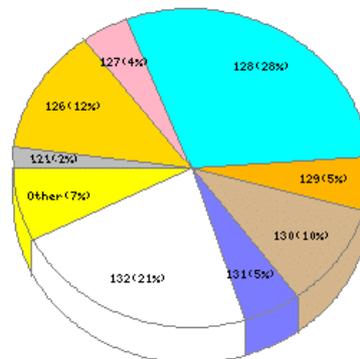
S Deposition: 0.32 keq/ha/yr



Plot Top Sources:

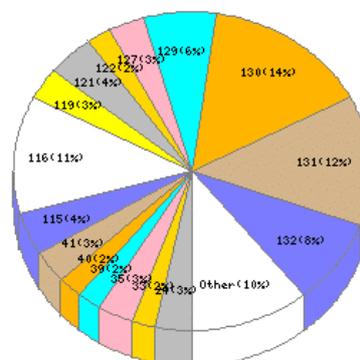
Source Attribution: [Search FootprintID](#)

N deposition (by footprint ID and %)



(Click on image to enlarge)

S deposition (by footprint ID and %)



(Click on image to enlarge)

Figure 3 – Results page from APIS showing feature information, critical loads and source attribution pie-charts.

5 ACKNOWLEDGEMENTS

We gratefully acknowledge funding of this project from the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER), Scottish Environment Protection Agency, Environment and Heritage Service, and the Environment Agency.

In addition we would like to thank the following experts that provided helpful advice during the course of this project: Clare Whitfield, Ian Strachan and Helen Baker (Joint Nature Conservation Committee), Caroline Chapman, Isobel Alonso, Keith Kirby, Richard Jefferson, Roger Meade, Ron Porley, Susan Watt, Sue Rees, Roger Morris, Ian Reach, Stewart Clarke and Alan Drewitt (English Nature), Linda Pope (the Environment Agency), and Darren Evans, René van der Wal and Kathy Hodder (Centre for Ecology and Hydrology).

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Appendix I

The following lists the columns present within the Excel database and some corresponding guidance to their meaning and application.

SACs

Site Code: All SAC have a UK site code

Site Name: The name of the site

Polygon ID Number: A number of polygons make up each site. These have been generated through GIS packages.

Suggested SSSI link: Some polygons are mapped to a particular SSSI. This can be very useful for local officers who are familiar with the smaller units of SSSI.

Designated Features: Each site and polygon is made up of key features (Annex 1 habitats or Annex 2 species) which are of relative importance in conservation value, representatively, biogeographical importance or population size or density.

Broad Habitat Type: Each Annex I habitat or Annex II species is allocated a Broad Habitat from the list of Biodiversity Action Plans.

Global Grade: The global assessment is an expert judgement of the overall value of the site for the conservation of the relevant Annex I habitat. Sites have been graded A, B or C:
A: Sites holding outstanding examples of the habitat in a European context.

B: Sites holding excellent stands of the habitat, significantly above the threshold for SSSI/ASSI notification but of somewhat lower value than grade A sites.

C: Examples of the habitat which are of at least national interest (i.e. usually above the threshold for SSSI/ASSI notification on terrestrial sites) but not significantly above this. These habitats are not the primary reason for SACs being selected.

Nitrogen Sensitivity: Ask the question is the designated feature sensitive to nitrogen deposition?

Acidity Sensitivity: Ask the question is the designated feature sensitive to nitrogen deposition?

UNECE (2003) Nitrogen Critical Loads class: The most relevant empirical critical load class was assigned against the Annex 1 habitat based on the 'best fit' of EUNIS classification codes.

Justification: Describes how the link was made between empirical critical load class and designated feature.

UNECE Nutrient class Impacts: Impacts of exceedance as laid out in the Berne report

Uncertainty: Uncertainty of the critical load range values are described in the Berne report as:

reliable: when a number of published papers of various studies show comparable results;

quite reliable: when the results of some studies are comparable;

expert judgement: when no data are available for this type of ecosystem. The nitrogen critical load is then based upon expert judgement and knowledge of ecosystems, which are likely to be more or less comparable with this ecosystem.

Empirical Critical Loads for Nitrogen Deposition: The critical load range values.

Acidity Class (UK NFC): The most relevant critical load habitat class (based on the 6 broad habitats from the National Focal Centre report) is assigned to each designated feature.

Acid Justification: Describes how the link was made between acidity critical load class and designated feature.

NFC Acidity classes Impacts: An indication of broad impacts from acidification of soils and freshwaters is given according to the broad habitat classes used by the National Focal Centre for Critical Loads.

Critical Load Function: The individual components of the critical load function are given (CLmaxS, CLminN and CLmaxN). Both a maximum and minimum range is given as described in section 3.2.1.

Notes: Any ecological or guidance notes.

Appendix II

SPA and SAC Annex II non-plant species

Site Code: All SACs and SPAs have a UK site code

Site Name: The name of the site

Polygon ID Number: A number of polygons make up each site. These have been generated through GIS packages.

Suggested SSSI link: Some polygons are mapped to a particular SSSI. This can be very useful for local officers who are familiar with the smaller units of SSSI.

Designated Features: Species under Annex 1 of the Birds Directive have been designated to a suite of SPAs based on the conservation requirements of each bird species. Annex II non-plant species fall under designations to SACs.

Layname: English common name

*Status:

B-Breeding,

W- Wintering,

P - Passage,

R - Resident

*Assemblage: Indicates whether the feature is a component of an assemblage (Waterfowl, Breeding or Seabird assemblage).

Broad Habitat: The broad habitat in which the feature resides. This can be more than one broad habitat depending on feeding, breeding or roosting habitats.

Habitat Notes: Notes on the broad habitat

Ecological Notes: Ecological notes of the species

Sensitive to Nutrient Nitrogen: Assesses whether the feature's broad habitat is sensitive to nutrient nitrogen.

Sensitive to Acidity: Assesses whether the feature's broad habitat is sensitive to acidification.

UNECE (2003) Nitrogen Critical Loads class: The most relevant empirical critical load class was assigned against the feature's broad habitat based on the 'best fit' of EUNIS classification codes.

Justification: Describes how the link was made between empirical critical load class and designated feature.

UNECE Nutrient class Impacts: Impacts of exceedance as laid out in the Berne report.

Species Effect?: By assessing the impacts of exceedance on the habitat, it is possible to weigh up whether these impacts are likely to have an impact on the specie's feeding, breeding or roosting requirements.

Justification: A justification for the above.

Uncertainty: Uncertainty of the critical load range values are described in the Berne report as:

reliable: when a number of published papers of various studies show comparable results;

quite reliable: when the results of some studies are comparable;

expert judgement: when no data are available for this type of ecosystem. The nitrogen critical load is then based upon expert judgement and knowledge of ecosystems, which are likely to be more or less comparable with this ecosystem.

Empirical Critical Loads for Nitrogen Deposition: The critical load range values.

Acidity Class (UK NFC): The most relevant critical load habitat class (based on the 6 broad habitats from the National Focal Centre for Critical Loads report) is assigned to each species broad habitat .

Acid Justification: Describes the link between acidity critical load class and species broad habitat.

Ecosystem Impacts: An indication of broad impacts from acidification of soils and freshwaters is given.

Species Effect?: By assessing the impacts of exceedance on the habitat, it is possible to weigh up whether these impacts are likely to have an impact on the species feeding, breeding or roosting requirements.

Justification: A justification for the above.

Critical Load Function: Where there is a potential impact on the species, the individual components of the critical load function are given (CLmaxS, CLminN and CLmaxN). Both a maximum and minimum range is given as described in section 3.2.1.

* applies to SPAs only.

PART II:
SOURCE ATTRIBUTION

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EXECUTIVE SUMMARY

1. The Fine Resolution Atmospheric Multi-pollutant Exchange model (FRAME) was applied to assess the magnitude and spatial distribution of individual deposition footprints of sulphur and nitrogen associated with gaseous emissions from 134 different point sources and background sources. The analysis was performed for a recent emissions year (2003) and for a future emissions scenario year (2010)
 - The 134 emissions sources considered in the study included:
 - SO₂ and NO_x emissions from 121 individual point sources and groups of point sources
 - SO₂ and NO_x emissions from 8 background emissions sectors
 - 3 NH₃ emissions sectors (livestock, fertiliser and non-agricultural)
 - Emissions from international shipping and from long range transport from European and background sources.
2. A number of model code modifications were necessary in order to obtain the most physically realistic representation of the deposition footprints from individual point sources. These included restraining the plume rise of emissions from point sources to prevent overshooting of the boundary layer and use of a non-directionally dependent wind speed of 7.5 ms⁻¹. A mass-conservative smoothing routine was applied to the model output data from point source simulations to avoid the 'wheel spoke effect' which occurs due to the divergence of trajectories as they move away from a point source.
3. A standard calibration procedure is routinely applied to model output data to compensate for the difference between modelled deposition data and maps of deposition generated from measurements. It was recognised that the application of the calibration procedure to deposition footprints from point sources could introduce non-realistic anomalies in the spatial distribution of deposition. Both calibrated and uncalibrated data were therefore supplied.
4. Data were generated at a 5 km resolution for the United Kingdom from 134 different model simulations. The species considered in the model output were wet deposition and vegetation-specific dry deposition of sulphur and oxidised and reduced nitrogen. Three different data formats were supplied: uncalibrated model data, calibrated model data and the percentage contribution of each source to total modelled deposition.
5. The data were generated in order to facilitate calculations of the contribution of individual sources to the exceedance of critical loads for acidic deposition and nutrient nitrogen deposition at a national scale.

1 INTRODUCTION

The Habitats Directive is transposed into national law by means of the Conservation (Natural Habitats & c.) Regulations 1994 (known as the Habitats Regulations). The Regulations specify the roles and responsibilities of public bodies (competent authorities), owners and occupiers, and the statutory advisors for nature conservation in meeting the obligations of the Habitats Directive. Under the Directive, licences are issued by the UK regulators (The Environment Agency in England and Wales, Scottish Environmental Protection Agency in Scotland and Department of Environment and Heritage in Northern Ireland). In meeting their obligation to avoid deterioration and/or significant disturbance to conservation sites by air pollution, there is a need to review existing decisions and consents (regulation 50) and assess the impact of these particularly in relation to acidification and the effects of nutrient nitrogen.

Under previous Environment Agency contracts, deposition output from the HARM and FRAME long range transport models were compared with site-relevant critical loads, which linked the national critical load data set for acidity and nutrient nitrogen to site specific conservation objectives for England and Wales. At the beginning of 2003 the Department for the Environment, Food and Rural Affairs (DEFRA) placed a new contract with CEH Edinburgh for the use of the FRAME model for air pollution policy evaluation for SO₂, NO_x and NH₃. In addition, revised national critical loads are now available and have been submitted to the UNECE as part of the ongoing assessment for the Gothenburg Protocol. In the light of these developments, the Environment Agency was motivated to revise its previous assessment to ensure that it was using the most up-to-date information. Although the previous work included the total emissions from Northern Ireland and Scotland, point sources were not specifically identified nor any estimation made of source attribution for acidic and nitrogen deposition in these areas. The revision of the assessment for England and Wales therefore also provides the opportunity to collaborate directly with SEPA and DoE (NI) to undertake a single assessment that is consistent across the UK. Ultimately, the output from this study will be used to help identify whether further controls on releases are required from processes controlled by the individual regulators.

2 DESCRIPTION OF THE FRAME MODEL

2.1 History

The FRAME (Fine Resolution Atmospheric Multi-pollutant Exchange) model is a Lagrangian atmospheric transport model used to assess the long-term annual mean deposition of reduced and oxidised nitrogen and sulphur over the United Kingdom. A detailed description of the FRAME model is contained in Singles et al. (1998). Fournier et al. (2002) describe the development of a parallelised version of the model with an extended domain that includes Northern Ireland and the Republic of Ireland. The model was developed from an earlier European scale model, TERN (Transport over Europe of Reduced Nitrogen, ApSimon et al. 1994). FRAME was developed initially to focus in particular on transport and deposition of reduced nitrogen and was named the Fine Resolution AMmonia Exchange model. Recent developments in the treatment of sulphur and oxidised nitrogen (Fournier et al., 2004) mean that it may now be considered as a robust multi-chemical species tool. The new name reflects these changes whilst preserving the familiar acronym. The current version of the model in use is FRAME 5.3.

The system used to generate UK maps of dry and wet deposition from site measurements of gas concentrations and wet deposition was previously referred to as the 'CEH deposition model'. This has now been named **CBED (Concentration Based Estimated Deposition)** to distinguish it from FRAME.

2.2 Model Domain

The domain of FRAME covers the British Isles with a grid resolution of 5 km and grid dimensions of 172 x 244. Input gas and aerosol concentrations at the edge of the model domain are calculated using **FRAME-EUROPE**, a larger scale European simulation which was developed from TERN to run a statistical model over the entirety of Europe with a 150 km scale resolution. FRAME is a Lagrangian model that simulates an air column moving along straight-line trajectories. The atmosphere is divided into 33 separate layers extending from the ground to an altitude of 2500 m. Layer thicknesses vary from 1 m at the surface to 100 m at the top of the domain. Separate trajectories are run at a 1° resolution for all grid edge points. A wind rose is used to give the appropriate weighting to directional deposition and concentration for calculation of total deposition and average concentration.

2.3 Emissions

Emissions of ammonia are estimated for each 5 km grid square using national data of farm animal numbers (cattle, poultry, pigs and sheep) as well as fertiliser application, crops and non-agricultural emissions (including traffic and contributions from human sources, wild animals etc). The ammonia emissions inventory is described in Dragosits *et al.* (1998). Emissions of SO₂ and NO_x are from the National Atmospheric Emissions Inventory for the United Kingdom (<http://www.naei.org.uk>). For SO₂, emissions from the UK are primarily associated with a small number of strong point source emissions. For NO_x, point source emissions are less significant than those from vehicle emissions, while NH₃ is emitted into the lowest layer.

2.4 Plume Rise

Point source emissions of SO₂ and NO_x are treated individually with a plume rise model which uses stack height, temperature and exit velocity to calculate an 'effective emissions height'. The plume reaches its maximum height when its temperature is equal to that of the surrounding environment and its momentum is dissipated. Buoyancy forces dominate the plume rise, which is parameterised separately for stable conditions and for neutral and unstable conditions according to the Pasquill-Gifford stability classes.

2.5 Diffusion

Diffusion of gaseous and particulate species in the vertical is calculated using K-theory eddy diffusivity and solved with a Finite Volume Method. The vertical diffusivity K_z has a linearly increasing value up to a specified height H_z and then remains constant (K_{max}) to the top of the boundary layer. During daytime, when diffusivity depends on a combination of mechanical and convective mixing, H_z is taken as 200 m and K_{max} is a function of the boundary layer depth and the geostrophic wind speed. At nighttime these values depend on the Pasquill stability class.

2.6 Chemistry

The chemical scheme in FRAME is similar to that employed in the EMEP Lagrangian model (Barrett and Seland, 1995). The prognostic chemical variables calculated in FRAME are: NH₃, NO, NO₂, HNO₃, PAN, SO₂, H₂SO₄, as well as NH₄⁺, NO₃⁻ and SO₄⁻ aerosol. For oxidised nitrogen, a suite of gas phase reactions are considered. These include photolytic dissociation of NO₂, oxidation of NO by ozone, formation of PAN (peroxyacetyl nitrate) and the creation of nitric acid by reaction with the OH· free radical. NH₄NO₃ aerosol is formed by the equilibrium reaction between HNO₃ and NH₃. A second category of large nitrate aerosol is present and simulates the deposition of nitric acid on to soil dust or marine aerosol. The formation of H₂SO₄ by gas phase oxidation of SO₂ is represented by a

predefined oxidation rate. H_2SO_4 then reacts with NH_3 to form ammonium sulphate aerosol. The aqueous phase reactions considered in the model include the oxidation of S(IV) by O_3 , H_2O_2 and the metal catalysed reaction with O_2 .

2.7 Wet Deposition

The model employs a constant drizzle approach using precipitation rates calculated from a climatological map of average annual precipitation for the British Isles. Wet deposition of chemical species are calculated using scavenging coefficients based on those used in the EMEP model. An enhanced washout rate is assumed over hill areas due to the scavenging of cloud droplets by the seeder-feeder effect. The washout rate for the orographic component of rainfall is assumed to be twice that calculated for the non-orographic component (Dore *et al.*, 1992). The model incorporates the directional dependence of orographic rainfall by considering two components of rainfall: non-orographic precipitation which has no directional dependence and orographic precipitation which is directionally dependent and stronger for wind directions associated with humid air masses. The directional orographic rainfall model is described in detail in Fournier *et. al*, (2001 and 2005).

2.8 Dry Deposition

Dry deposition of SO_2 , NO_2 and NH_3 is calculated individually to five different land categories (arable, forest, moor-land, grassland and urban). For ammonia, deposition is calculated individually at each grid square using a canopy resistance model (Singles *et al.*, 1998). The deposition velocity is generated from the sums of the aerodynamic resistance, the laminar boundary layer resistance and the surface resistance. Dry deposition of SO_2 and NO_2 is calculated using maps of deposition velocity derived by the CEH 'big leaf' model (Smith *et al.* 2000), which takes account of surface properties as well as the geographical and altitudinal variation of wind-speed. Other species are assigned constant values of deposition velocity.

2.9 Diurnal Cycle

The depth of the boundary layer in FRAME is calculated using a mixed boundary layer model with constant potential temperature capped by an inversion layer with a discontinuity in potential temperature. Solar irradiance is calculated as a function of latitude, time of the year and time of the day. At nighttime, a single fixed value is used for the boundary layer depth according to Pasquill stability class and surface wind speed.

2.10 Wind Rose

The wind rose employed in FRAME uses 6-hourly operational radiosonde data from the stations of Stornoway, Hillsborough, Camborne and Valentia spanning a ten-year period (1991-2000) to establish the frequency and harmonic mean wind speed as a function of direction for the British Isles. This is illustrated in figures 1(a) and 1(b) for data averaged over the ten year period.

2.11 Computational Performance

The model code is written in High Performance FORTRAN 90 and executed in parallel on a Linux Beowulf cluster comprising of 60 dual processors. Run time for a simulation employing 100 processors is approximately 25 minutes.

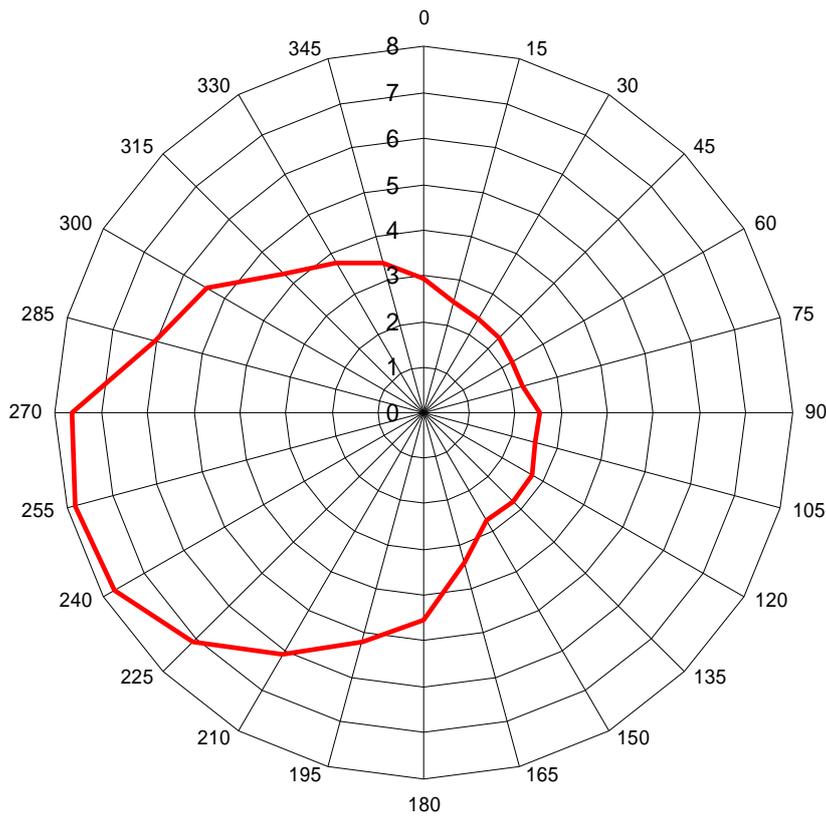


Figure 1(a) Wind frequency rose

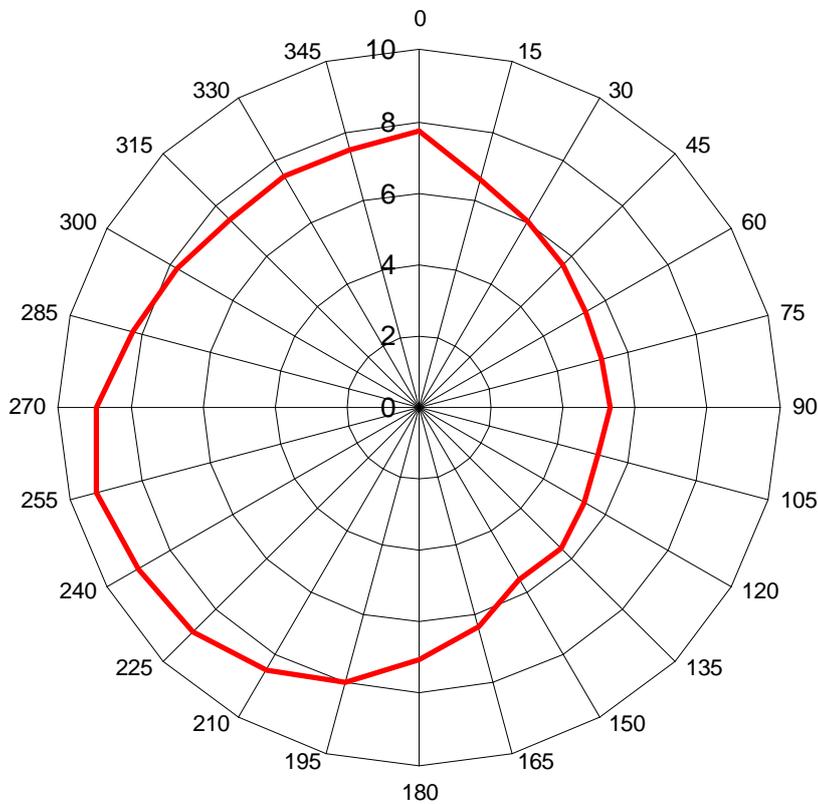


Figure 1(b) Windspeed rose

3 LINEARITY TEST

In order to investigate whether the deposition of sulphur and nitrogen in FRAME responds linearly to abatement of emissions, a single point source was selected to test abatement of sulphur and oxidised nitrogen emissions for a variety of different abatement levels. The point source (OS coordinates 365300, 304200) was chosen as being representative of a medium-sized source (with annual emissions of 4.8 kT S-SO₂ and 1.6 kT N-NO₂). It had a high stack height of 204 m and high emissions velocity of 28 m s⁻¹. A further advantage taken in to account when choosing this site was its relatively central location. Many large point sources are located on the east coast of the UK. Due to the strong weighting of winds to the south-west, the deposition footprint due to emissions from such sources will be largely exported over the north sea. A source with a more westerly location is therefore considered desirable in this test in order that the deposition footprint will occur principally over the U.K. land mass.

Eleven simulations were run with abatement of emissions from the point source of 0, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100% whilst emissions from all other sources were unchanged. The changes in total deposition of oxidised nitrogen were found to be strongly linearly related to the changes in emissions, as illustrated in Figure 2. With a 10% abatement, total NO_y deposition decreased by 0.0242 kT N whereas with a 100% abatement of emissions, total deposition decreased by 0.242 kT N. The response of the deposition of sulphur to changes in emissions showed a small deviation away from a linear response. With a 10% abatement, deposition decreased by 0.207 kT S whereas with a 100% abatement there was a decrease in deposition of 2.25 kT S, marginally greater than that which would be predicted for a perfectly linear relationship with emissions abatement.

This test illustrates a strong degree of linearity between abatement of emissions of SO₂ and NO_x and changes in deposition. It suggests therefore that the percentage abatement applied in a study to attribute sources to spatial deposition will not have a strong influence on final results. It can therefore be concluded that a 100% abatement may be applied for establishing the deposition footprints. The resultant deposition footprint can be used to estimate the influence of applying smaller abatements by simple linear scaling.

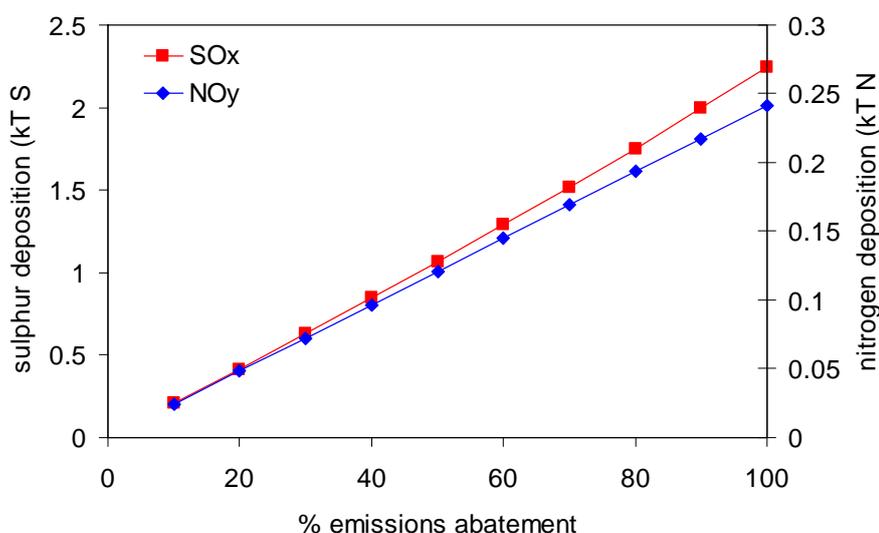


Figure 2. Change in nitrogen and sulphur deposition budgets for a point source with variable emissions abatements.

3.1 Description of modelling technique applied to source attribution FRAME runs

FRAME was used to estimate the contribution to deposition of sulphur and nitrogen across the United Kingdom for 134 different sets of emissions data, including individual point sources and background emissions of SO₂, NO_x and NH₃. Two sets of emissions scenarios were considered, one representing a recent year (2003), and the second for a future year, 2010, when nation states are required to meet the emissions targets specified by the Gothenburg protocol and the National Emissions Ceiling Directive. A detailed inventory of emissions from 242 individual point sources for the year 2003 was provided by the Environment Agency, the Scottish Environmental Protection Agency and Environment Heritage Service Northern Ireland. The data included, where available, information on stack height, diameter, temperature and exit velocity of emissions, as well as annual emissions of SO₂ and NO_x. Where stack parameters were missing, typical default values were assigned to major point sources. The individual stacks were grouped into 120 different emissions sources, based on their site location and corporate ownership. Remaining emissions of SO₂ and NO_x were taken from the National Atmospheric Emissions Inventory (NAEI) using data for the most recent emissions year available, 2002. These included a further 766 small point sources as well as gridded background emissions for different SNAP codes (Selected Nomenclature for Air Pollution): Energy production and transformation; Commercial, institutional and residential combustion; Industrial combustion; Industrial processes; Production and distribution of fossil fuels; Road transport; Other transport; Waste treatment and disposal.

The input of ammonia emissions to the model used the updated spatial AENEID inventory of Dragosits *et al.* (1998) that separately calculates spatial emissions from cattle, pigs, poultry, sheep, crops and grassland and non-agricultural sources. Background emissions of SO₂, NO_x and NH₃ were scaled to give the correct totals for the year 2003 according to the NAEI estimates. The emissions scenario for the year 2010 was generated by modifying the 2003 scenario. Planned changes to emissions from individual large point sources were applied. Abatement factors were applied to each snap code for background sources according to business-as-usual future emissions estimates supplied by the NAEI. The set of 132 FRAME model runs executed is described in Table 1. The changes in emissions from the point sources between the years 2003 and 2010 are illustrated in Table 2.

3.2 Parameterisations employed in FRAME for the source-attribution simulations

The development of improved parameterisations in numerical models is generally driven by the need to apply the models to new problems. The FRAME model has previously been applied to estimating total deposition patterns from all sources of NH₃, NO_x and SO₂ in the United Kingdom. In the present source attribution project, FRAME has been applied to investigate deposition patterns from single elevated sources. This difference results in a number of issues concerning the behaviour of the model which were identified following the initial set of simulations:

1. The plume rise and vertical mixing in the model was sensitive to the diurnal cycle;
2. The plume rise and vertical mixing in the model was sensitive to the advection wind speed which was itself a function of wind direction (Figure 1(b));
3. A 'wheel-spoke effect' was observed whereby trajectories diverged at a certain distance away from a point source. This effect is not important when modelling all SO₂ sources together, rather than a single one.
4. For certain trajectories, with high point sources, it was possible for emissions to break through the boundary layer.

Whilst the last effect can occur in certain meteorological conditions, it was considered inappropriate to include it in a statistical Lagrangian model where the effect occurred for certain trajectories but not for others. It was also considered that the plume rise and vertical mixing in the model responded in an over-sensitive way to directionally dependent wind speed that could produce unrealistic effects in deposition pattern.

For the present study, it was decided to:

1. Restrain the plume rise to within the boundary layer
2. Apply a symmetric wind speed rose with the mean wind speed (7.5 ms^{-1})
3. Apply a post-processing smoothing routine to the deposition data for the point source abatement simulations only (numbers 1 to 118)

The smoothing routine involved assigning the average deposition from the nine points in a three by three grid and assigning this value to the central point. This process is mass conservative and is effective in removing the wheel-spoke effect without distorting a deposition footprint. The effect of applying the smoothing routine is illustrated in Figure 3 for the SO_y dry deposition footprint for Point Source 39.

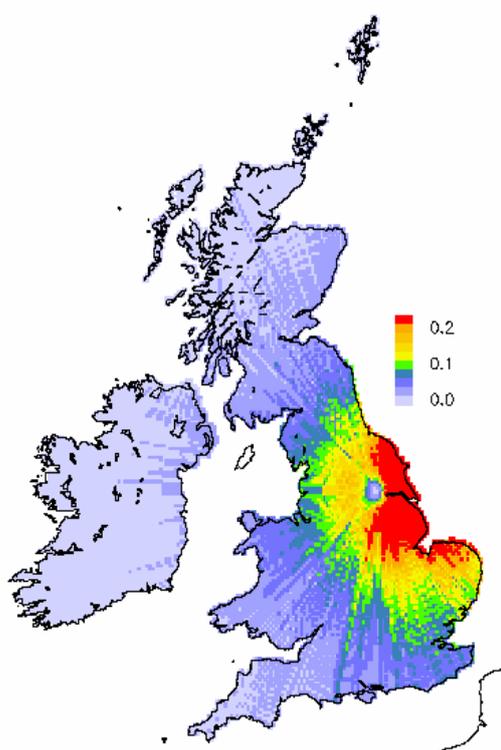


Figure 3(a) Footprint for dry deposition of SO_y

For Point Source 39 with no smoothing ($\text{kg S ha}^{-1} \text{ yr}^{-1}$)

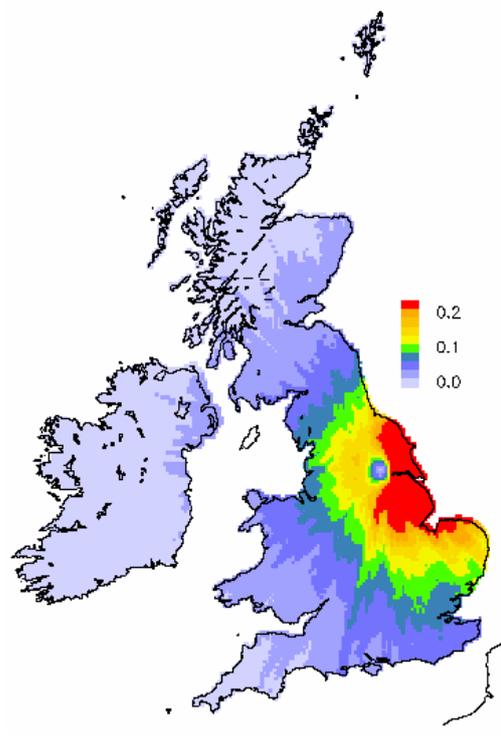


Figure 3(b) Footprint for dry deposition of SO_y

For Point Source 39 with smoothing ($\text{kg S ha}^{-1} \text{ yr}^{-1}$)

Table 1 - Description of abatement measures applied in the FRAME simulations

Simulation number (id)	Description of abatement measure	Abatement factors for 2010
0	Baseline simulation (no abatement)	Abatement applied per SNAP sector
1-118	SO ₂ and NO _x emissions from major point sources	New 2010 emissions applied to around 30 sources. No abatement applied to the remainder.
119	SO ₂ and NO _x emissions from minor point sources	SO ₂ : 0.96; NO _x : 0.99
120	Other SO ₂ and NO _x emissions from SNAP sector 1 (energy, production and transformation)	SO ₂ : 0.36; NO _x : 0.73
121	Other SO ₂ and NO _x emissions from SNAP sector 2 (commercial, institutional and residential combustion)	SO ₂ : 0.23; NO _x : 0.95
122	Other SO ₂ and NO _x emissions from SNAP sector 3 (industrial combustion)	SO ₂ : 0.96; NO _x : 0.99
123	Other SO ₂ and NO _x emissions from SNAP sector 4 (industrial processes)	SO ₂ : 1.36; NO _x : 1.79
124	Other SO ₂ and NO _x emissions from SNAP sector 5 (production and distribution of fossil fuels)	SO ₂ : 1.00; NO _x : 0.71
125	Other SO ₂ and NO _x emissions from SNAP sector 6 (solvents)	SO ₂ : 1.00; NO _x : 1.00
126	Other SO ₂ and NO _x emissions from SNAP sector 7 (road transport)	SO ₂ : 1.00; NO _x : 0.56
127	Other SO ₂ and NO _x emissions from SNAP sector 8 (other transport)	SO ₂ : 0.89; NO _x : 0.88
128	NH ₃ emissions from livestock	NH _x : 0.96
129	NH ₃ emissions from fertilisers	NH _x : 0.96
130	NH ₃ emissions from non-agricultural sources	NH _x : 0.96
131	SO ₂ emissions from shipping	SO ₂ : 1.00; NO _x : *
132	All imported 'background' emissions	SO ₂ : 0.58; NO _x : 0.78

* No shipping emissions data for NO_x

Table 2 - Emissions from point sources for years 2003 and 2010

2003 SO ₂ emissions (kT S)	2003 NO _x emissions (kT N)	2010 SO ₂ emissions (kT S)	2010 NO _x emissions (kT N)
450	158	317	141

The footprints of dry and wet N and S deposition corresponding to each source were calculated according to equation (1) by the difference between the deposition maps for the baseline simulation (id=0) and a simulation with the emissions removed (id=n):

$$FP_{(id=n)} = DEP_{(id=0)} - DEP_{(id=n)} \dots\dots\dots (1)$$

where FP is the footprint and DEP is the FRAME modelled deposition data.

Where FRAME deposition data are to be used for calculations of critical loads exceedance, a standard technique is to apply a ‘calibration procedure’ (NEGTA, p91). This approach is based on the convention that the official data set of mapped deposition of nitrogen and sulphur for the United Kingdom is obtained from measurements of wet deposition and gas concentrations for recent years. The CBED data set (Concentration Based Estimated Deposition) is averaged over the three-year period 1998-2000. FRAME may be used to provide estimates of deposition for future years (i.e. using projected emissions change to inventories for the year 2010). In estimating changes in pollutant deposition over time, it is important to compare equivalent data sets. Comparing FRAME deposition estimates for the year 2010 with CBED deposition for the period 1998-2000 could result in misleading conclusions due to the differences in the approaches used. It is for this reason that a calibration is applied to FRAME deposition to normalise the modelled data to the CBED estimates. In essence ‘calibration’ means that FRAME is used to estimate the relative change to deposition for each 5 km grid square in the UK during a specified time period. Future estimates of deposition are calculated by applying the modelled change to the CBED measurement-based deposition for a recent year for each individual UK 5km grid square. For this work, the calibration procedure used is described in equation (2):

$$DEP_{(CAL,2010)} = DEP_{(UNC,2010)} * (DEP_{(CBED,1998-2000)}/DEP_{(UNC,1999)}) \dots\dots\dots (2)$$

where $DEP_{(UNC,1999)}$ refers to uncalibrated FRAME deposition data for the emissions simulation year 1999, $DEP_{(UNC,2010)}$ refers to uncalibrated FRAME deposition data for the emissions simulation year 2010, $DEP_{(CBED,1998-2000)}$ is the CBED deposition data for the period 1998-2000 and $DEP_{(CAL,2010)}$ is the calibrated deposition for the year 2010.

In this work, the goal was to allocate deposition of nitrogen and sulphur to different sources for each model 5 km grid square. The use of the calibration procedure can also be applied to the footprint data generated according to equation (1). For calibration of footprints, the formula applied is described in equation (3).

$$FP_{(CAL,2010,id=n)} = FP_{(UNC,2010,id=n)} * DEP_{(CAL,2010)} / \sum FP_{(UNC,2010,id=1,132)} \dots\dots\dots (3)$$

Where $\sum FP_{(UNC,2010,id=1,132)}$ corresponds to the sum of the uncalibrated footprints. This calibration procedure ensures that the calibrated footprints, when combined, will generate the official deposition totals for the year 2010. An identical calibration procedure was applied for the years 2003 and 2010, according to equation (3). In practice, the sum of the footprints for NO_x and SO_y deposition was calculated for simulations 1-127 and 131-134 (those concerning abatement of NO_x and SO_y emissions) whilst for NH_x deposition, the footprint sum was calculated for the simulations involving abatement of NH_x emissions (128, 129 and 130 only). Following analysis of the calibrated footprint data, it was recognised that the calibration procedure could introduce anomalies into the deposition footprints due to the geographically variable ratio of deposition for CBED :FRAME. An example is illustrated for Source 24 in Figure 4. It is evident that the calibration procedure results in relocation of the areas of peak deposition away from the source in a non-

realistic manner, for example with increased deposition in London. It was therefore decided to supply the deposition in three separate formats, allowing flexibility in the subsequent application of the data for source attribution purposes. The three data sets supplied were:

1. Uncalibrated deposition footprints (normalised such that the sum of the footprints was equal to the baseline simulation with no abatement of emissions applied).
2. Calibrated deposition footprints (normalised such that the sum of the footprints was equal to the calibrated baseline simulation with no abatement of emissions applied).
3. Percentage footprints (formatted to calculate the fractional contribution to the total deposition contributed by each source).

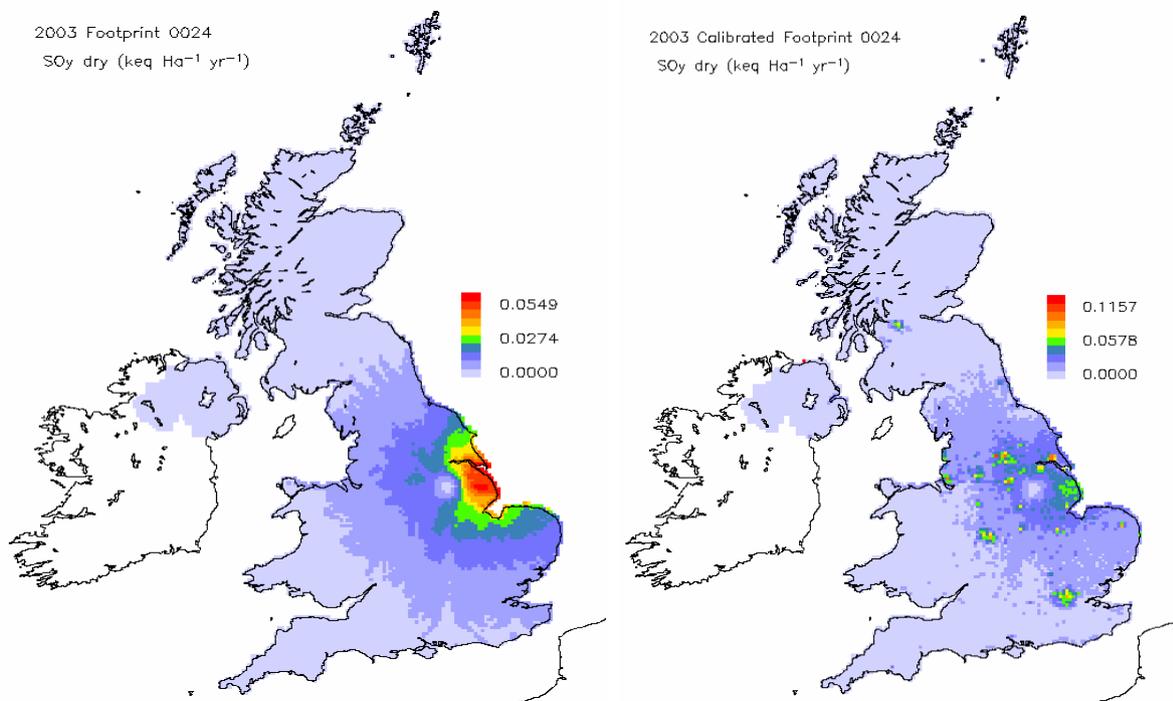


Figure 4(a) Uncalibrated SO₂ deposition for Source 24 (keq ha⁻¹ yr⁻¹)

Figure 4(b) Calibrated SO₂ deposition for Source 24 (keq ha⁻¹ yr⁻¹)

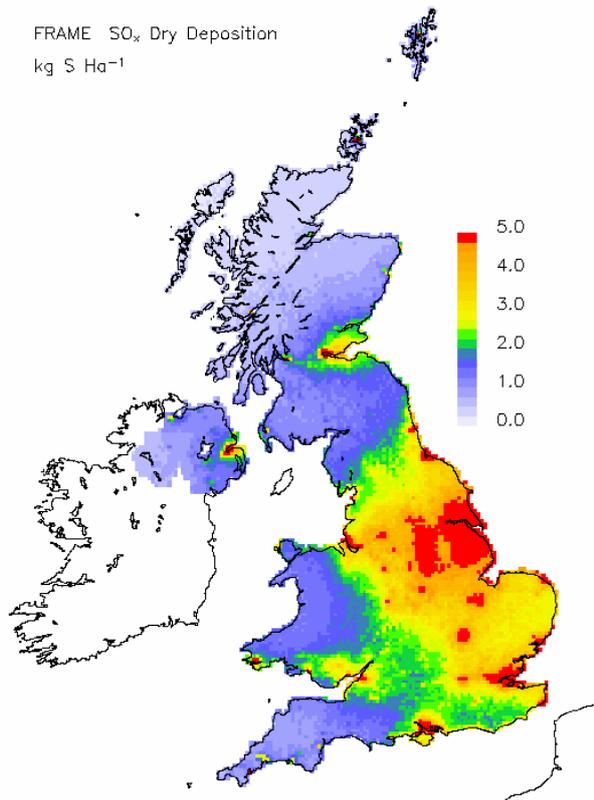
4 RESULTS AND DISCUSSION

4.1 Maps of Total Deposition

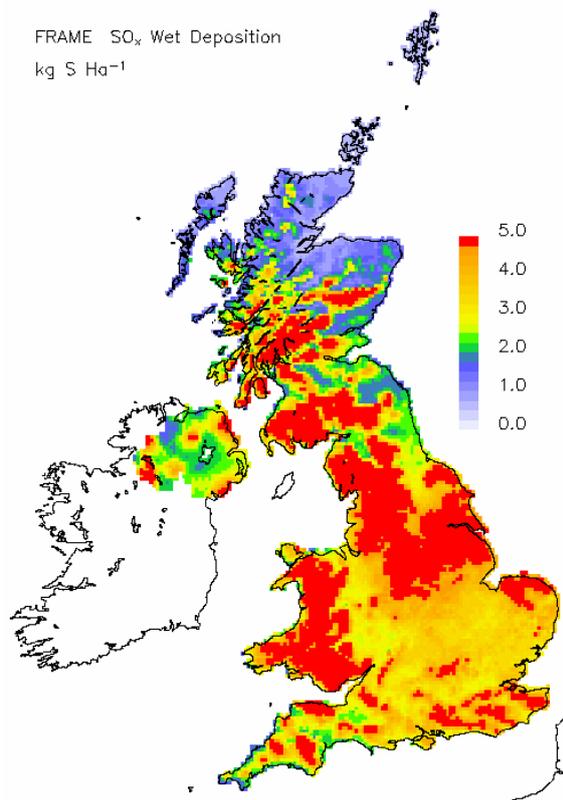
The model maps of wet and dry deposition of sulphur and reduced and oxidised nitrogen for Simulation 0 with no sources abated are illustrated in Figure 5.1 for the year 2003 and in Figure 5.2 for the year 2010. Dry deposition of sulphur (Figure 5.1(a)) is highest in the industrial area of northeast England. Wet deposition is associated with longer-range transport of sulphate aerosol and is highest in the hill and source regions with heavy precipitation in northern England and Wales (Figure 5.1(b)). The dry deposition of NO_y (Figure 5.1(c)) is closely associated with the major urban conurbations of Greater London, Birmingham and Manchester as well as the interlinking motorways. In Figure 5.1(d) it can be seen that wet deposition of NO_y is linked particularly with the hill regions of northern England and Wales. Unlike SO_2 and H_2SO_4 , NO and NO_2 are insoluble so that washout of the primary oxidised nitrogen pollutants near to source is insignificant. Wet deposition of oxidised nitrogen is associated with nitric acid and nitrate aerosol, which are secondary pollutants, formed over longer distance scales. Due to its low emission height, primarily from livestock, and its high deposition velocity, ammonia is dry deposited close to source and shows strong spatial variability (Figure 5.1(e)). Wet deposition of reduced nitrogen (Figure 5.1(f)) is mostly due to washout of ammonium aerosol, a secondary pollutant associated with long-range transport, and highest, as with oxidised nitrogen, in the hill areas of northern England and Wales. Comparison of figures 5.1 and 5.2 shows the decreasing trend in S and N deposition between 2003 and 2010 with a marked decrease in the areas where both wet and dry deposition of sulphur and oxidised nitrogen exceeds $5 \text{ kg S ha}^{-1} \text{ yr}^{-1}$ and $5 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ respectively.

4.2 Deposition footprints for a point source

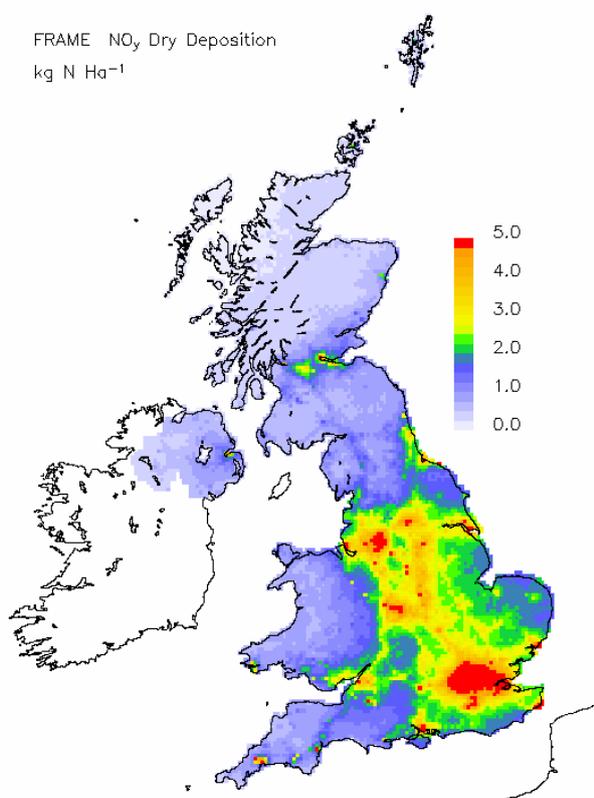
The majority of the FRAME model simulations were aimed at identifying the deposition footprints of sulphur and nitrogen deposition from single point sources or groups of point sources controlled by a single operator. These data are most important for sulphur deposition, as power stations and industrial combustion from point sources are the main contributors to sulphur emissions in the United Kingdom. The contribution of these sources to NO_x emissions is significant, but less important than the contribution from vehicles. The uncalibrated deposition footprints of wet and dry deposition of sulphur and oxidised nitrogen for Point Source 64 are illustrated in Figure 5.3. These figures illustrate the typical features of deposition from a point source. The dry deposition of both NO_y and SO_y is highest in the vicinity of the source, with a greater contribution to acidic deposition being made by sulphur. The highest areas of wet deposition of NO_y occur, however, in more distant hill areas where the washout of secondary nitrate aerosol is highest. Due to the solubility of SO_2 and H_2SO_4 , however, wet deposition of SO_y is high close to the source.



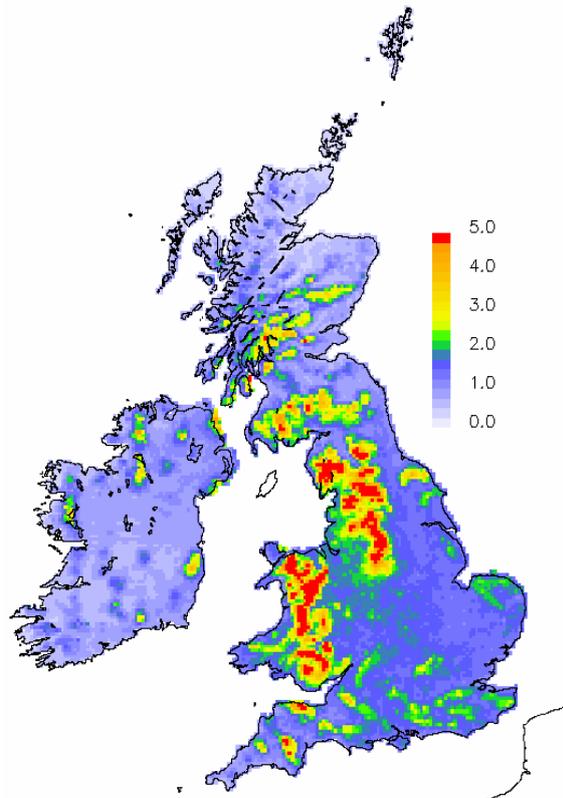
**Figure 5.1(a) 2003 uncalibrated
FRAME SO_y dry deposition
(kg S ha⁻¹ yr⁻¹)**



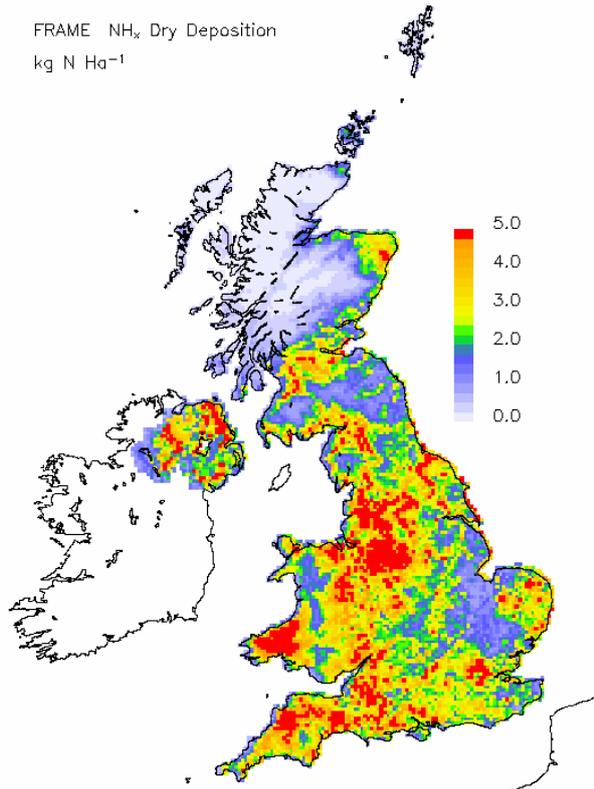
**Figure 5.1(b) 2003 uncalibrated
FRAME SO_y wet deposition
(kg S ha⁻¹ yr⁻¹)**



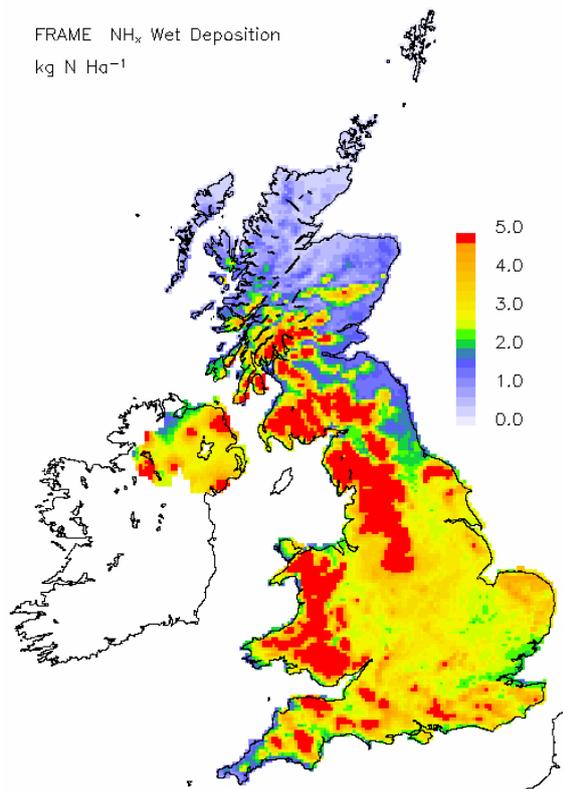
**Figure 5.1(c) 2003 uncalibrated
FRAME NO_y dry deposition
(kg N ha⁻¹ yr⁻¹)**



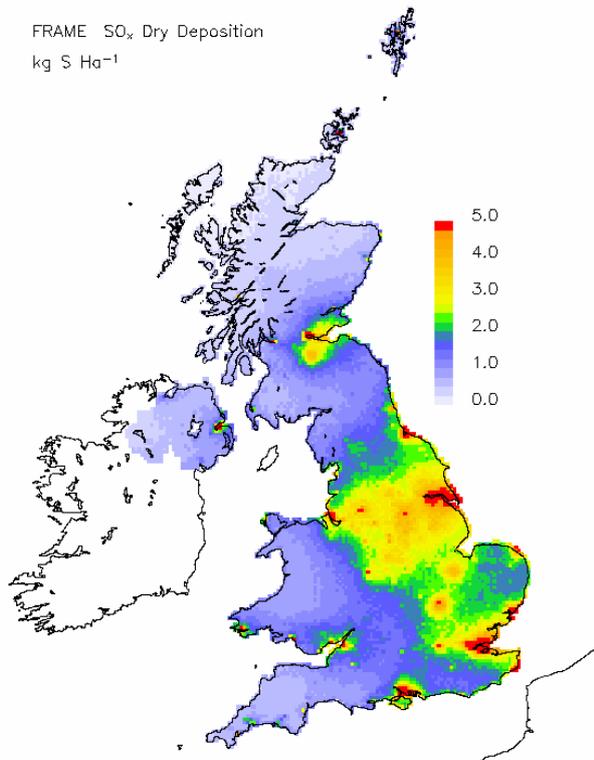
**Figure 5.1(d) 2003 uncalibrated
FRAME NO_y wet deposition
(kg N ha⁻¹ yr⁻¹)**



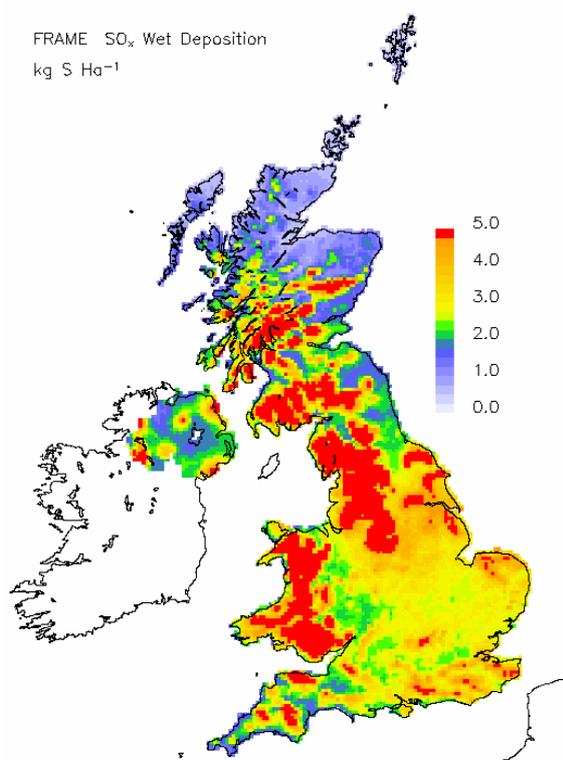
**Figure 5.1(e) 2003 uncalibrated
FRAME NH_x dry deposition
(kg N ha⁻¹ yr⁻¹)**



**Figure 5.1(f) 2003 uncalibrated
FRAME NH_x wet deposition
(kg N ha⁻¹ yr⁻¹)**



**Figure 5.2(a) 2010 FRAME
uncalibrated SO_y dry deposition
(kg S ha⁻¹ yr⁻¹)**



**Figure 5.2(b) 2010 FRAME
uncalibrated SO_y wet deposition
(kg S ha⁻¹ yr⁻¹)**

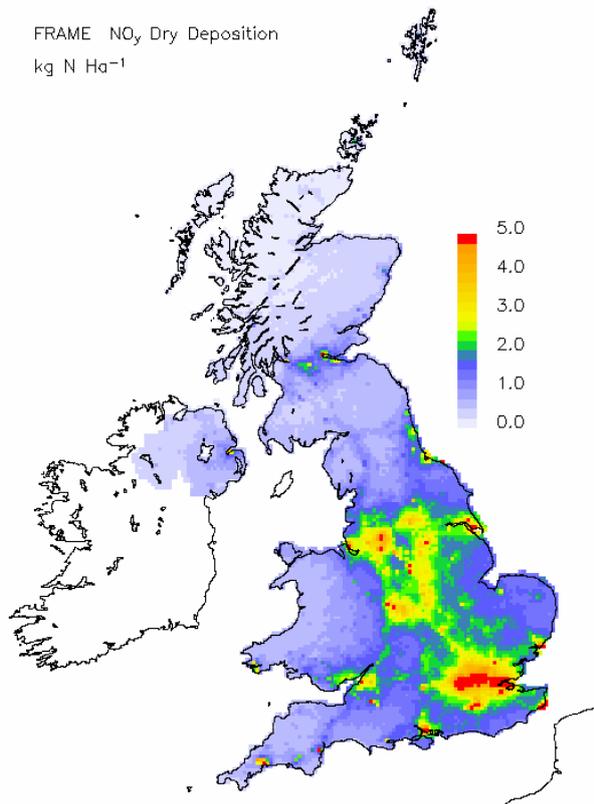


Figure 5.2(c) 2010 FRAME uncalibrated NO_y dry deposition (kg N ha⁻¹ yr⁻¹)

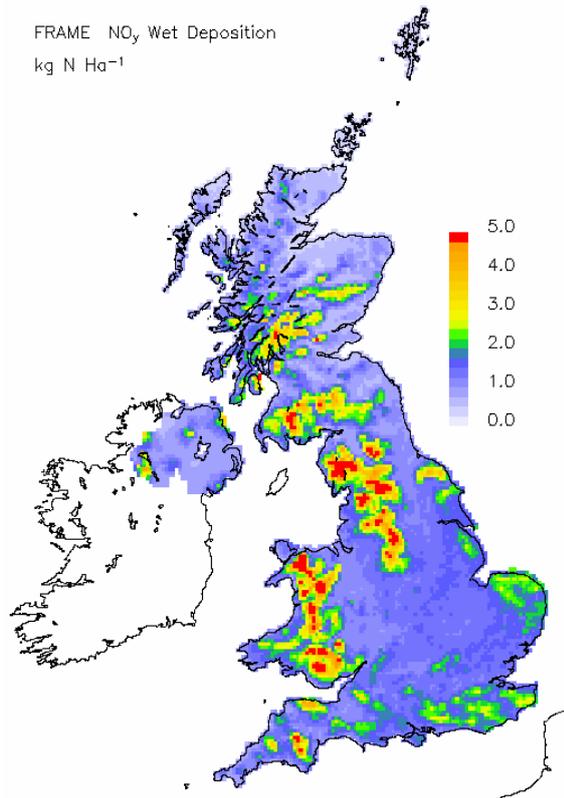


Figure 5.2(d) 2010 FRAME uncalibrated NO_y wet deposition (kg N ha⁻¹ yr⁻¹)

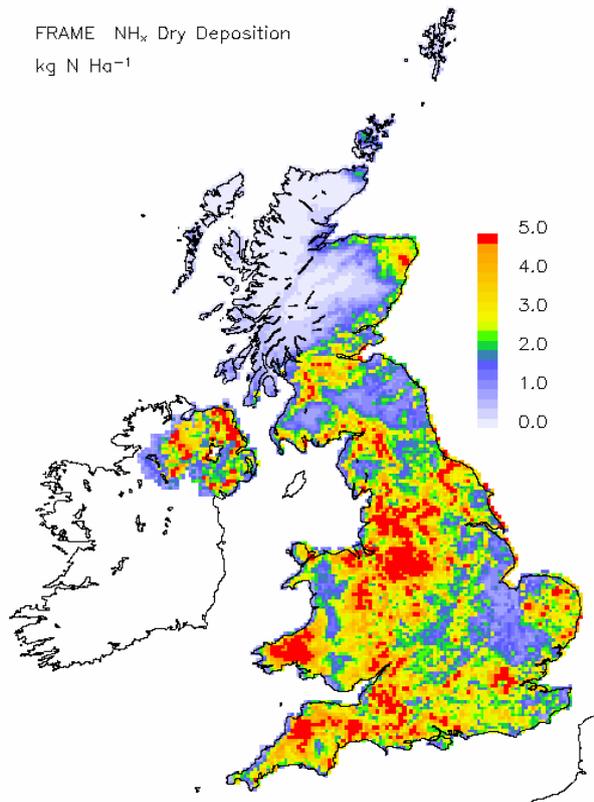


Figure 5.2(e) 2010 FRAME uncalibrated NH_x dry deposition (kg N ha⁻¹ yr⁻¹)

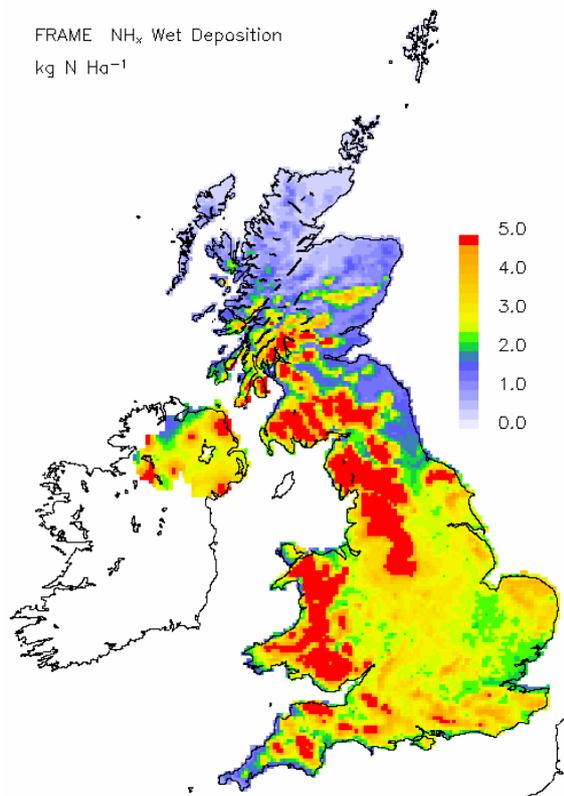


Figure 5.2(f) 2010 FRAME uncalibrated NH_x wet deposition (kg N ha⁻¹ yr⁻¹)

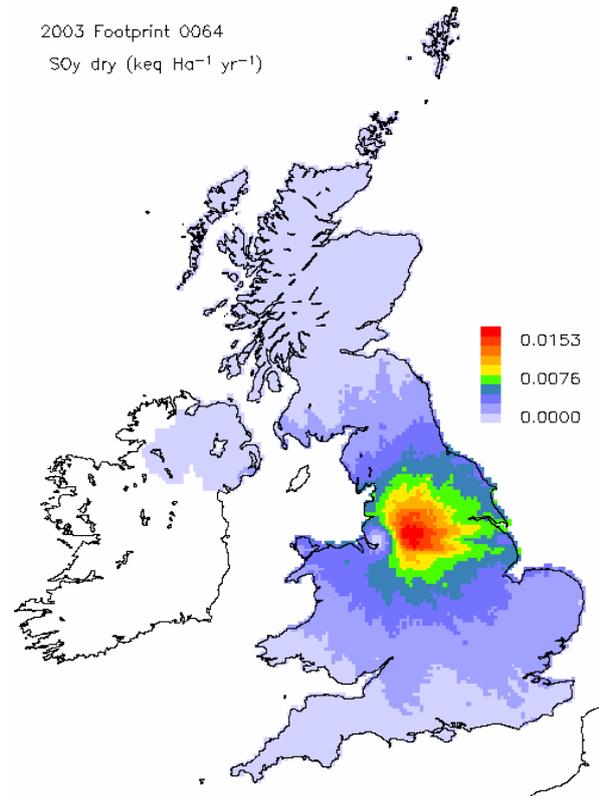


Figure 5.3(a) Uncalibrated FRAME SO_y dry deposition footprint for Source 64 (keq ha⁻¹ yr⁻¹)

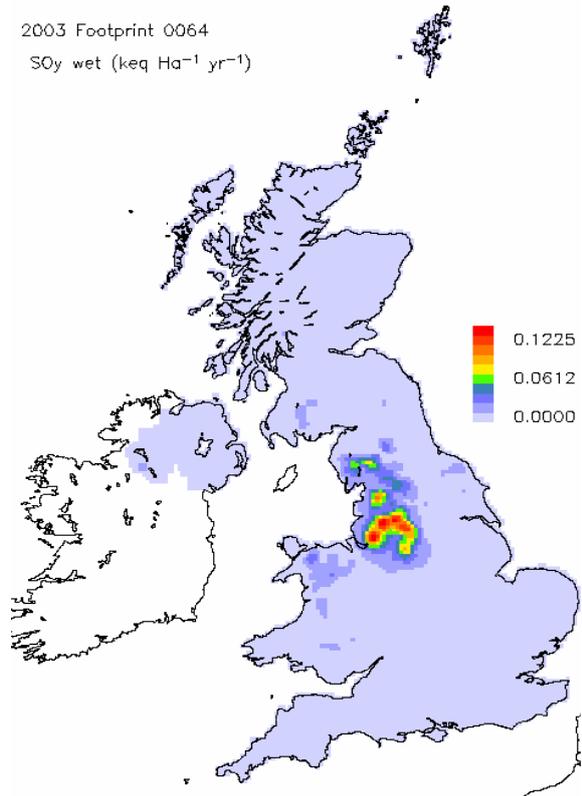


Figure 5.3(b) Uncalibrated FRAME SO_y wet deposition footprint for Source 64 (keq ha⁻¹ yr⁻¹)

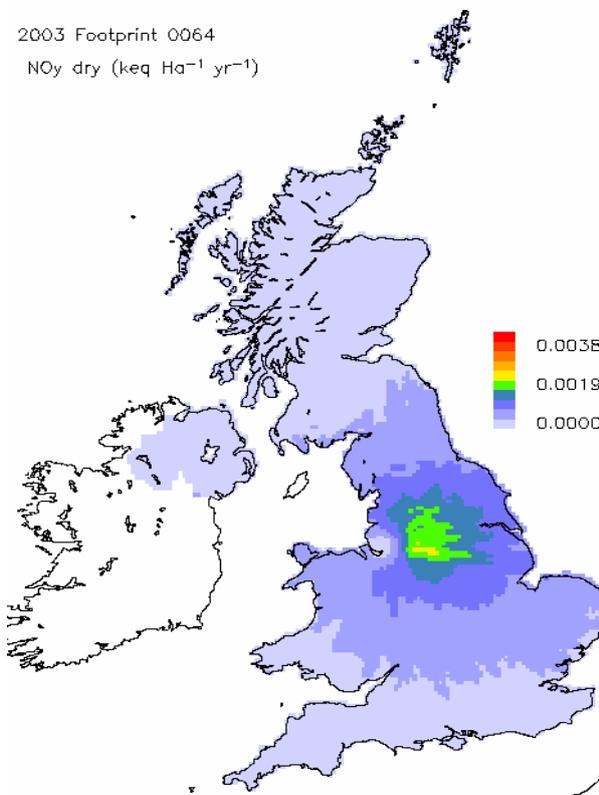


Figure 5.3(c) Uncalibrated FRAME NO_y dry deposition footprint for Source 64 (keq ha⁻¹ yr⁻¹)

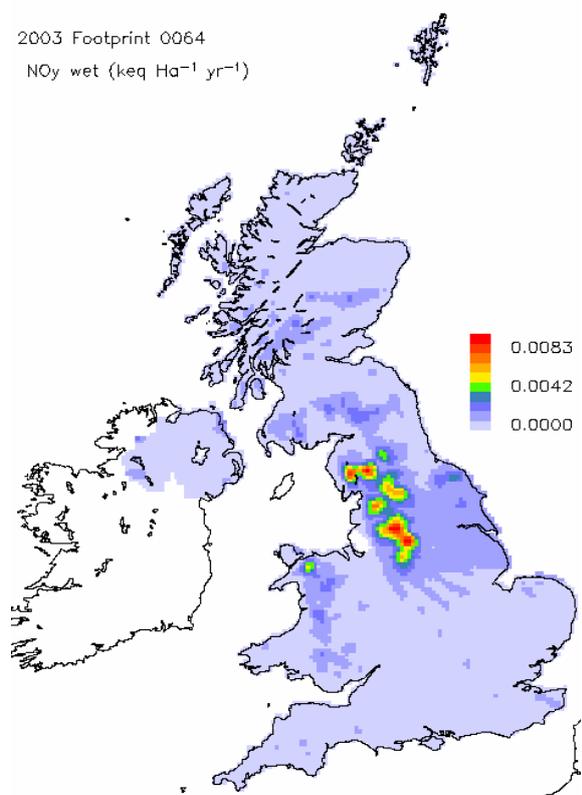


Figure 5.3(d) Uncalibrated FRAME NO_y wet deposition footprint for Source 64 (keq ha⁻¹ yr⁻¹)

4.3 Deposition footprints for background sources

The distinction between 'point source' emissions and 'background' emissions is not a formal one. The allocation of an emissions source into one or other of these categories depends on the procedures of emissions reporting and mapping. With improving emissions reporting procedures in place, the list of sources allocated as point sources tends to increase. For the present study, 886 point sources were considered. Of these, 242 sources were allocated to 120 different groups (simulations 1-118 and 133-134). The remaining 644 'small point sources' were treated as a single group (Source 119). The footprint for these small point sources is illustrated in Figure 5.4(a). It can be seen that small point sources contribute to sulphur deposition primarily in the areas of northern England and greater London.

The most important source of NO_x emissions in the United Kingdom is road transport. The footprint of NO_y deposition from road transport (Source 126) is illustrated in Figure 5.4(b). The influence of the main urban conurbations (London, Birmingham, Manchester, Glasgow) and the inter-connecting motorways (M1, M4, M6, M74) is clearly evident.

Ammonia emissions are currently all categorised as background sources. These have been divided into three sectors: livestock (Simulation 128), fertiliser (Simulation 129) and non-agricultural (Simulation 130). Dry deposition of reduced ammonia from livestock has a strongly variable pattern, with significant sources from pigs and poultry in East Anglia and north-east England and emissions from cattle making a major contribution in western England (Figure 5.4(c)). Emissions of ammonia from fertiliser application account for approximately 10% of total ammonia emissions in the United Kingdom. The deposition footprint from fertilisers makes a significant contribution across the country as shown in Figure 5.4(d). Non-agricultural sources also make a significant contribution to ammonia emissions, comprising a mixed set of sources, including emissions from vehicles with catalytic convertors, pets, sewage treatment, wild animals, babies' nappies, human sweat and cigarette smoke. These sources are most concentrated in major urban areas, as is evident from the footprint for reduced nitrogen dry deposition illustrated in Figure 5.4(e). Figure 5.4(f) shows the contribution to sulphur dry deposition from emissions from shipping (Simulation 131). This is highest in south east England due to heavy shipping in the English channel. In Figure 5.4(g), the wet deposition of NO_y from imported sources is illustrated. These include European emissions, emissions from the republic of Ireland (which is represented explicitly in the FRAME domain) and global background concentrations. The long range transport component of pollutants is predominantly in the particulate form which features as a contribution to wet deposition, particularly in the hill regions and also in south-east England.

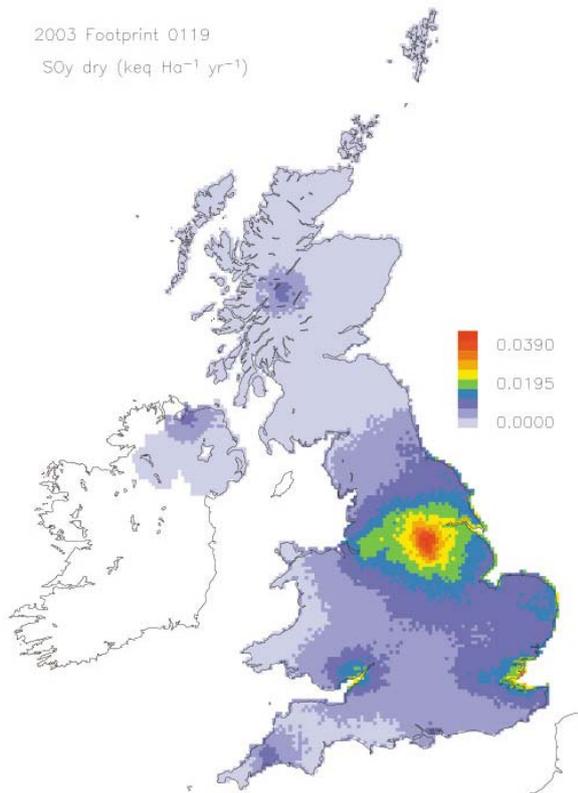


Figure 5.4(a) Uncalibrated FRAME SO_y dry deposition footprint for Source 119: Minor point sources (keq ha⁻¹ yr⁻¹)

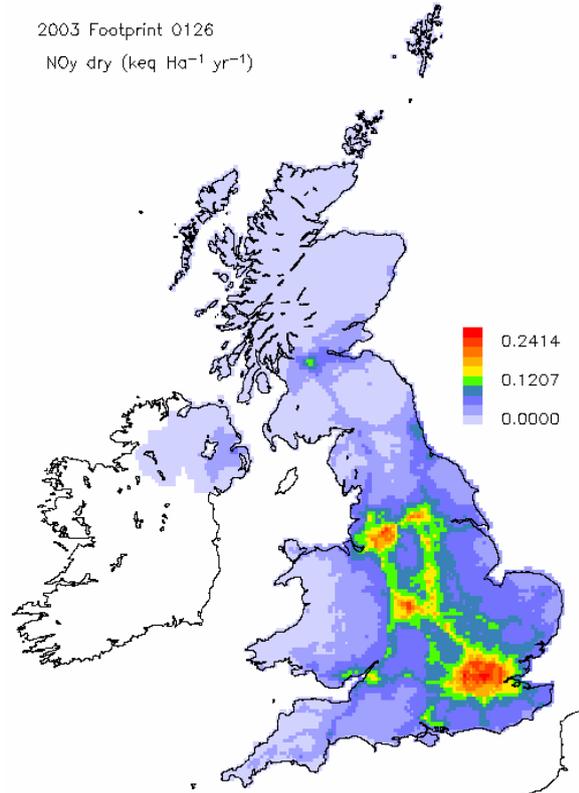


Figure 5.4(b) Uncalibrated FRAME NO_y dry deposition footprint for Source 126: Road transport (keq ha⁻¹ yr⁻¹)

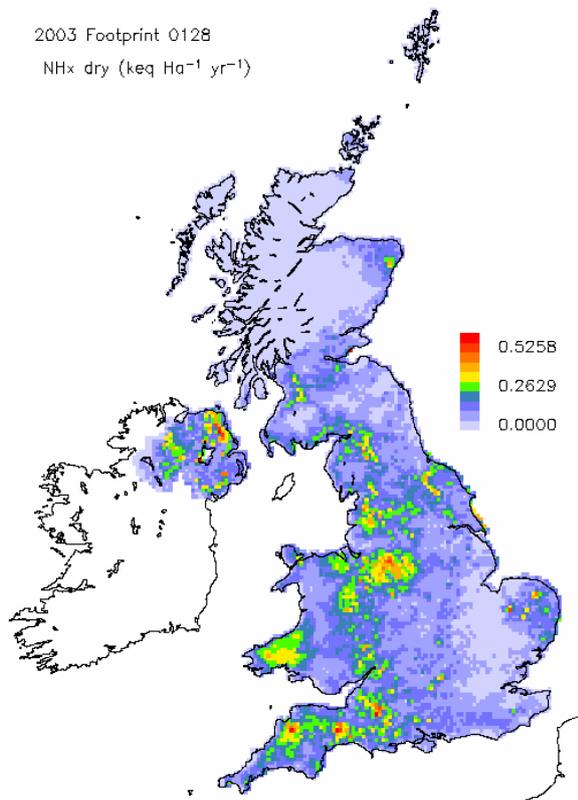


Figure 5.4(c) Uncalibrated FRAME NH_x dry deposition footprint for Source 128: Livestock (keq ha⁻¹ yr⁻¹)

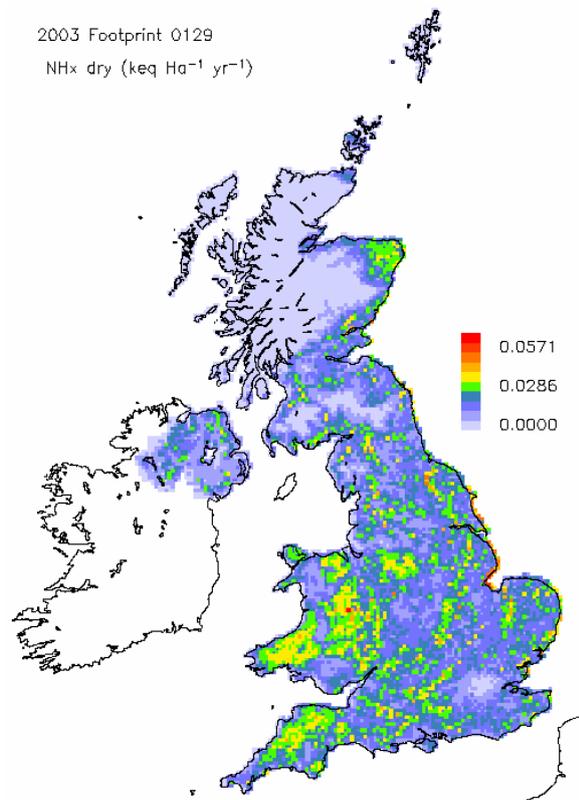


Figure 5.4(d) Uncalibrated FRAME NH_x dry deposition footprint for Source 129: Fertiliser (keq ha⁻¹ yr⁻¹)

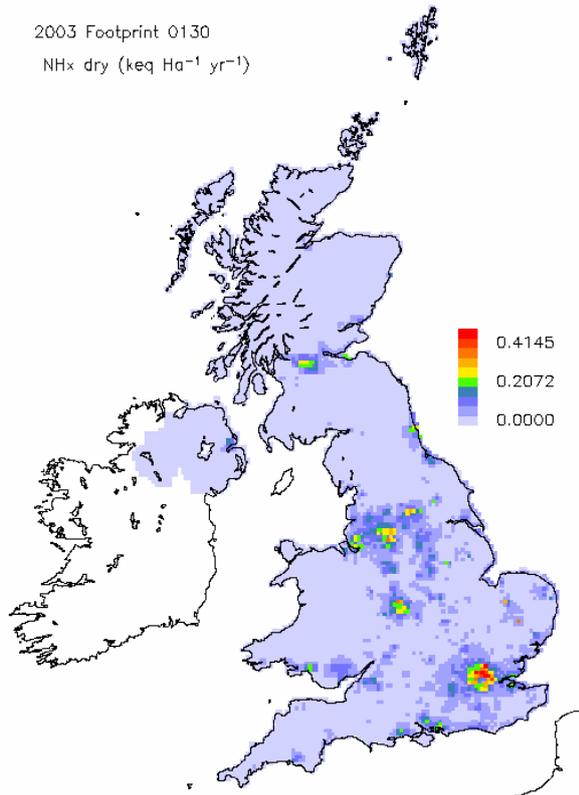


Figure 5.4(e) Uncalibrated FRAME NH_x dry deposition footprint for Source 130: Non-agricultural sources (keq ha⁻¹ yr⁻¹)

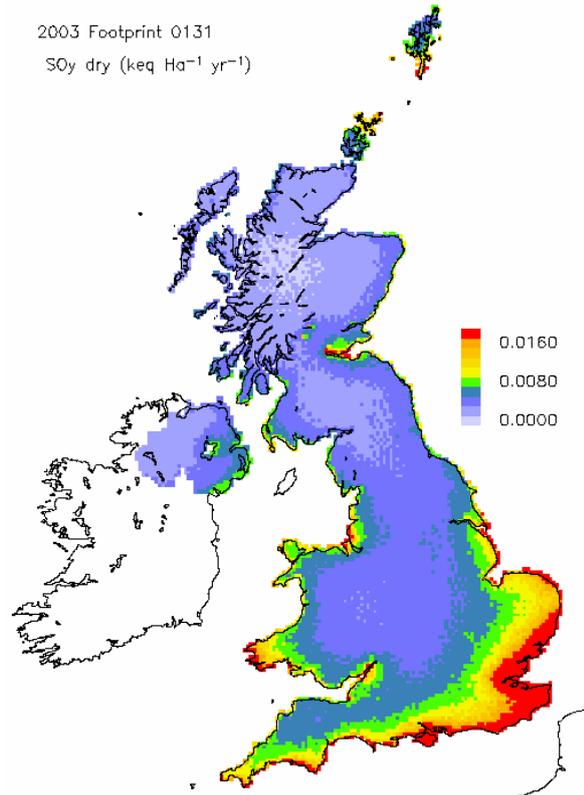


Figure 5.4(f) Uncalibrated FRAME SO_y dry deposition footprint for Source 131: Shipping (keq ha⁻¹ yr⁻¹)

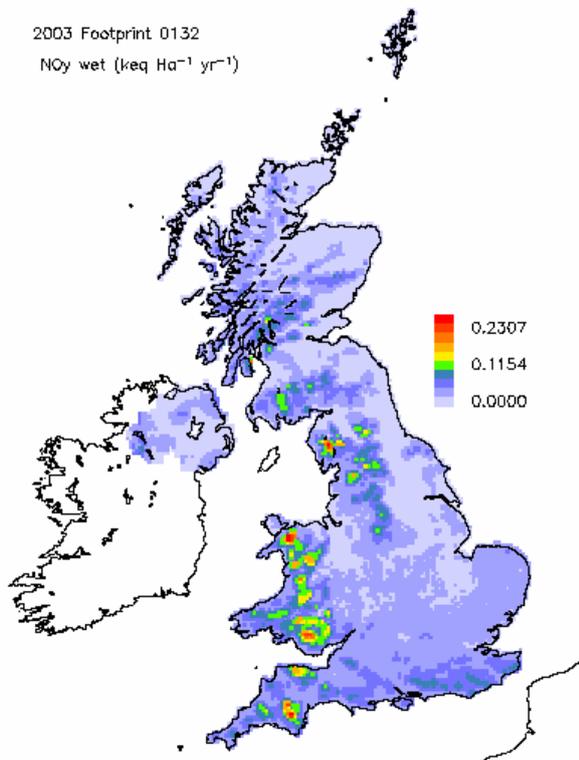


Figure 5.4(g) Uncalibrated FRAME NO_y wet deposition footprint for Source 132: Import (keq ha⁻¹ yr⁻¹)

5 APPLICATION OF THE MODEL RESULTS

The data obtained from this study will be used for quantitative assessment of the influence of emissions abatement from individual sources on exceedances of critical loads for acidic deposition and nutrient nitrogen deposition. For each 5 km model grid square in the UK, the relative contribution of individual sources to pollutant deposition has been calculated. The database generated in this study will be used to develop an effective strategy for emissions abatement to protect the natural environment in Special Protection Areas and Special Areas of Conservation from the effects of acidification and eutrophication.

6 ACKNOWLEDGEMENTS

We gratefully acknowledge funding of this project from the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER), Scottish Environment Protection Agency, Environment and Heritage Service, and the Environment Agency.

We would like to thank Colin Powlesland from the Environment Agency, Colin Gillespie from the Scottish Environmental Protection Agency and David Bell from Environment Heritage Service Northern Ireland for providing data on emissions and stack parameters from major point sources in England and Wales, Scotland and Northern Ireland respectively.

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