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Evidence Project Final Report

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Project identification

1. Defra Project code: AC0109
2. Project title: Future patterns of ammonia emissions across the UK and the potential impact of local emission reduction measures
3. Contractor organisation(s): NERC Centre for Ecology & Hydrology; Rothamsted Research North Wyke; Imperial College
4. Total Defra project costs (agreed fixed price): £ 199,938
5. Project: start date 1-Apr-2007
   end date 31-Dec-2012

6. It is Defra's intention to publish this form.

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n/a

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

1. Objectives

The aim of this project was to investigate possible future developments of the spatial distribution of ammonia (NH_3) emissions in the UK and how protection of designated sites could be maximised by different options to meet different national and international commitments. In summary, the objectives and related key questions to be answered by the project were:

- To develop detailed scenarios of the spatial distribution of NH_3 emissions for 2020, taking account of information on future projections. - ***How will ammonia emissions, concentrations, N deposition and their effects on designated sites (SACs, SSSIs) change towards 2020?***
- To construct scenarios of possible spatial variation of NH_3 emissions in relation to more efficient approaches for the future protection of designated sites, with the aim of maximising protection for the minimum amount of emission reduction, and to quantify results with high resolution modelling of spatially distributed NH_3 concentrations, N deposition and Critical Levels (CLE) and Loads (CL) exceedance at UK and landscape scales. - ***What effect would NH_3 mitigation scenarios of different ambition have on CLE/CL exceedance of designated sites? How powerful could spatially targeted mitigation be in improving outcomes for designated sites? Could taking account of the relative spatial location of local NH_3 sources and SACs/SSSIs be a cost-effective solution for protecting designated sites?***
- To investigate approaches by which the findings of local scale (sub-grid) variability assessment and strategies can be implemented, for more effective benefits of local spatial strategies. - ***How could spatially targeted measures be implemented locally, and what might they look like?***

2. Methods

2.1. Mitigation measures and scenario development - Ammonia (NH_3) emission mitigation scenarios were developed using 'business as usual' projections for the year 2020 as a baseline (FAPRI, 2011), together with the latest available UK NH_3 emission inventory methodology (Misselbrook *et al.* 2011). All scenarios were assessed for exceedance of NH_3 CLEs, and selected scenarios for nutrient N CLs.

Critical Load analyses were carried out both for all UK habitats and for N-sensitive SACs/SSSIs, at a 1km grid resolution. Two main approaches are taken for the development of mitigation scenarios:

- UK-wide (uniformly distributed) application of mitigation measures
- Spatially targeted application of measures to maximise cost-benefit for SACs/SSSIs, using a) buffer zones of different widths surrounding the sites, b) testing current spatially targeted schemes (Nitrate Vulnerable Zones) for effectiveness for NH_3, and adding tree belts near NH_3 emission sources to reduce atmospheric NH_3.

2.2. UK scale assessment - UK scale assessment of future patterns of ammonia emissions, concentrations, deposition and CL and CLE exceedance was carried out using the suite of Defra national tools, models and datasets (NARSES agricultural emission model, AENEID spatial emission model, FAPRI projections of livestock populations and fertiliser use, UK FRAME atmospheric transport model, and the most recent empirical methodology for CL/CLE assessments). A novel aspect of the project was the development and use of UK models at a 1km grid resolution rather than the usual 5 km grid assessment. Threats to sensitive habitats from atmospheric NH_3 were quantified for the scenarios by applying the CLEs both UK-wide and specifically to SACs and SSSIs, focusing on the 3 µg NH_3 m^{-3} threshold (for higher plants), but also analysing model output for the 1 µg NH_3 m^{-3} CLE (for the most sensitive receptors, such as lichens and mosses). Different indicators were used to quantify the % of designated sites exceeding a Critical Level, following the approach of Hallsworth *et al.* (2010).

2.3. Landscape scale assessment - For the landscape scale assessment, detailed spatial data on agricultural management and nitrogen inputs for existing study landscapes were available from previous projects (NERC GANE/LANAS, NitroEurope IP). These landscapes represent a range of typical agricultural systems in the UK, such as arable, poultry, dairy, beef and sheep farming, interspersed with sensitive habitats. Field- and farm based emissions were calculated using the same emission factors as for the UK scale assessment, however with detailed local farm management information taken into account. The Local Area Dispersion and Deposition (LADD) Model was used for deriving NH_3 concentration maps, and CLE assessment of the landscape scenarios was carried out in the same way as at the UK scale.

3. Results, Implications & policy recommendations

How will ammonia emissions, concentrations, N deposition and their effects on designated sites (SACs, SSSIs) change towards 2020?

- Ammonia emissions and concentrations are estimated to change very little towards 2020, given predictions of future livestock populations and fertiliser application rates under business-as-usual scenarios and the current limited ambitions for mitigation. This is expected to result in little change on effects of atmospheric NH_3 for SACs/SSSIs. Further substantial planned reductions in NO_x deposition are estimated to decrease overall N deposition and CL exceedance towards 2020. However, deposition from agricultural NH_3 sources across the UK is predicted to decrease by only by small amounts, similar to NH_3 concentrations.

What effect would NH_3 mitigation scenarios of different ambition have on CLE/CL exceedance of designated sites?

- NH_3 mitigation measures need to be ambitious if Critical Level/Critical Loads exceedances are to be substantially reduced, both UK-wide and for SACs and SSSIs.
- It should be noted that there are significant differences between UK-wide results and the individual countries (compared with each other and with the UK-wide results) which could result in different conclusions in each case. The difference between the baseline scenarios and the measures is much greater for England, than UK-wide, for example, suggesting that it is not appropriate to consider the data at the UK level alone.

How powerful could spatially targeted mitigation be in improving outcomes for designated sites?

- Effective spatially targeting of measures around designated sites is expected to result in substantial reductions in NH_3 concentrations and dry deposition originating from local sources.

Due to the longer transport distances and correlation with high rainfall/upland areas, reducing wet deposition requires larger overall reductions in NH_3 emissions over wider areas, and spatial targeting is less effective here, i.e. substantial national and international measures are required.

- It can be inferred from the scenario work that a mixed approach, combining UK-wide mitigation measures of modest ambition with locally targeted measures of higher ambition near sensitive conservation sites, would result in protecting the largest numbers and areas of SACs/SSSIs and UK semi-natural vegetation.

Could taking account of the relative spatial location of local NH_3 sources and SACs/SSSIs be a cost-effective solution for protecting designated sites?

- Spatially targeted mitigation can be achieve reductions in NH_3 CLE exceedance at SACs/SSSIs that are nearly large as UK-wide mitigation scenarios, with the spatially targeted measures achieving a much higher cost effectiveness (by a factor of 3-7, depending on the scenario).
- The higher cost-effectiveness of spatially targeted measures is due to the rapid decrease in NH_3 concentrations away from intensive sources and the close spatial interplay of sources and nature conservation areas in the UK. Spatially targeted mitigation can also help reduce NH_x dry deposition near sensitive sites close to sources.

How could spatially targeted measures be implemented locally, and what might they look like?

- Spatially targeted measures could be implemented locally via incentive schemes for land management change, such as the successor to current agri-environment schemes for the period 2014-20, by adapting existing options for atmospheric NH_3 and targeted appropriately. This could include buffer zones of low-emission agriculture or extensification, application of technical measures, as well as agro-forestry measures through strategic tree planting.
- The UK scale modelling is representative at the national scale, however local conditions need to be taken into account on the ground for maximising benefits of measures for individual sites. There is substantial potential for establishing a general framework for such an approach, which could be developed in collaboration between the conservation agencies, government, farmers, farm advisors, local authorities, etc. At the individual designated site level, locally tailored decisions are needed, taking account of the designated features and their location, local and regional emission sources and conditions such as prevailing winds and topography.

4. Further actions resulting from research (Knowledge exchange)

- Two ammonia seminar days were held, in London and Edinburgh, bringing together policy staff from government departments (Defra and devolved administrations) and the different agencies (incl. JNCC, EA, SEPA, NIEA, NE, SNH, FC), organised by this project. The events included presentations from this and two related projects (AC0201 Agroforestry Systems for Ammonia Abatement, AC0103 Agricultural NH_3 emissions as a source of UK secondary aerosol and the effect of emission abatement measures), preceded by an introduction on the role of NH_3 in the UK pollution climate and spatial/temporal trends (RoTAP, 2012).
- A further knowledge exchange event held was held through Webinar format, requested by for Natural England. Feedback from these events has been used to improve this report.
- Scientific papers are being drafted from this work, for publication in the peer-reviewed literature (UK scenario modelling, landscape).

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;

- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Exchange).

Original project objectives (inc. changes during project lifetime, as agreed with Defra project officer)

The aim of this project was to investigate possible future developments of the spatial distribution of ammonia emissions in the UK and how these are influenced by options to meet different national and international commitments. Specifically, the stated objectives were:

1) To develop detailed scenarios of the spatial distribution of NH_3 emissions for future years (e.g. 2010, 2020) taking account of information on future projections of activity data, and to compare these with existing simpler mitigation scenarios based on overall emissions ceilings.
2) To construct scenarios of possible spatial variation of NH_3 emissions in relation to more efficient approaches for the protection of SSSIs (incl. ASSIs in Northern Ireland) and SACs for future years, with the aim of maximising the protection in target habitats for the minimum amount of emission reduction.
3) To provide these spatial emissions scenarios at a high spatial resolution for the application of the UK FRAME model, calculating NH_3 concentrations and N deposition and assessing the extent and spatial distribution of exceedance of critical loads and critical levels.
4) To vary the emission scenarios, considering the outcomes of ecosystem protection, total magnitude of emissions (i.e. national ceilings), links to other policies and overall costs in order to assess the sensitivity and robustness of protection targets.
5) To test the local application of mitigation strategies through local scale atmospheric emission and dispersion modelling at existing case study sites (from NERC GANE/LANAS and NitroEurope projects).
6) To investigate possible protection distances for SSSIs and SACs in relation to emission magnitude, farm and field management practices, risk of ecological effects and different regulatory contexts (e.g. degree of precaution in Habitats Directive vs. SSSIs etc).
7) To investigate approaches by which the findings of local scale (sub-grid) variability assessment and strategies can be incorporated quantitatively into national scale modelling, for more effective reporting of the benefits of local spatial strategies.

All main objectives stated above were met, with some changes in the finer detail, by agreement with the Defra project officer (by objective numbers).

Ad 1) More scenarios for 2020 were investigated, instead of scenarios being repeated for additional years.
Ad 2 and 3) All UK modelling was carried out at a 1 km grid resolution throughout, rather than a mixture of 1 km and 5 km resolution, which benefited the assessment of Critical Level and Critical Load exceedance, due to the better resolved spatial distribution of source and sink areas.
Ad 4) UK NH_3 mitigation costs were considerably out-of-date, therefore the UK Integrated Assessment Model (UKIAM) was not suitable for use in this project. However, a targeted NH_3 mitigation costs workshop (led by Helen ApSimon) during summer 2012 allowed cost estimates to be built into the NARSES emission inventory calculations and mapping, enabling the derivation of cost estimates for all mitigation scenarios.
Ad 6) A planned single stakeholder workshop was replaced with two stakeholder seminar days on NH_3, held in London (Nov 2012) and Edinburgh (Feb 2013), allowing policy-relevant output from this project to be presented in conjunction with the results from other related Defra projects.

1. Policy context and scientific background

Currently, UK policy on ammonia (NH_3) in the UK is focused on meeting national emissions ceilings under the UNECE Gothenburg Protocol and the complementary National Emissions Ceilings Directive (NECD). Possible measures have been aimed at modest emission reductions across the country under broad national strategies, with little consideration of the spatial patterns of such reductions or the consequences of the spatial pattern of mitigation on protected sensitive semi-natural vegetation.

In this context, it is important to take account of trends and projections for emission sources and their spatial patterns, to evaluate the effectiveness of potential measures into the future. For this project, the year 2020 was agreed to provide a suitable time frame, with detailed projections on the main NH_3 sources, livestock populations and fertiliser application trends, available (FAPRI, 2011), in addition to projected NO_x and SO_2 emissions (Misra *et al.*, 2012), which are needed to a) calculate total nitrogen (N) deposition for assessing the exceedance of Critical Loads and b) to represent the overall pollution climate taking account of chemical interactions in the atmosphere.

The achievement of environmental improvement for ecosystems is typically measured as a reduction in the exceedance of "critical loads" for atmospheric N deposition or "critical levels" for atmospheric NH_3 concentration, i.e. thresholds for risk of adverse ecological impacts, according to current knowledge. Due to successful mitigation efforts for SO_2 and NO_x and resulting reductions in emissions in the UK (and across Europe) during the last two to three decades, the area of natural ecosystems with exceedance of the Critical Loads (CL) for acidity decreased from 75% in 1995-97 to 49% in 2009-2011, with the average accumulated exceedance (AAE[1]), halving during this period. However, area exceedances of the Critical Loads for nutrient N during the same period only reduced from 75% to 68%, with the average AAE decreasing by only 20%, with large areas of semi-natural habitats still exceeding the Critical Loads adopted by the UNECE (2010).

For NH_3, less abatement has so far been achieved compared with SO_2 and NO_x. Exceedance of the Critical Levels (CLE; UNECE, 2007) for atmospheric concentrations of NH_3 is also widespread across the country. A modest reduction in NH_3 emissions of less than 20% has been achieved since 1990, which is mainly due to decreasing livestock populations rather than implementation of abatement measures. The exception to this is intensive pig and poultry farming, where Best Available Technology (BAT) is required under the IPPC Directive. However, at a landscape scale, such farms are often NH_3 "hotspots" in the countryside, due to their size, and there is a continuing trend towards larger farm sizes and clusters of intensive livestock housing. This means that while total NH_3 emissions from intensive farming may have decreased at the national scale, problems of NH_3 hot spots will have increased in many places. Other UK farm types, such as cattle farms (the largest UK NH_3 source) have very few incentives to reduce their NH_3 emissions under current legislation. In these situations, the only drivers to reduce NH_3 emissions are the incentive to reduce fertiliser bills or other local environmental concerns (such as nature protection).

Realistic mitigation strategies need to identify priorities for the protection of sensitive habitats and species, as comprehensive protection of all sensitive vegetation in the UK from NH_3 and N pollution effects would require very drastic measures. (This shows that the target under the EC 6^{th} Environmental Action Programme for no-significant adverse effects by 2010 is not feasible.) For this project, the focus was on maximising protection of N-sensitive Special Areas of Conservation (SACs) under the Habitats Directive and UK Sites of Special Scientific Interest (SSSIs, or Areas of Special Scientific Interest (ASSIs) in Northern Ireland)[2]. Throughout this report, the term SSSIs will be used for simplicity, except when refering specifically to Northern Irish sites. This project provides an opportunity to test whether the spatial prioritisation of mitigation in the vicinity of protected sites would maximise environmental benefits, especially for NH_3 CLE exceedance, for a given investment.

Such approaches of targeting mitigation where this provides the most benefit, rather than applying less ambitious measures evenly across the whole country, would also be expected to reduce total costs to farmers for a given level of environmental improvement. To be able to quantify the potential effectiveness of measures for individual protected sites, both national scale and landscape scale, assessments need to be made of the spatial patterns of emissions and effects, due to the large spatial variability of NH_3 at all scales.

Key questions:

From the original proposal, a number of key questions were defined, to be answered by the project:

1) How will ammonia emissions, concentrations, N deposition and their effects on designated sites (SACs, SSSIs) change towards 2020?
2) What effect would NH_3 mitigation scenarios of different ambition have on CLE/CL exceedance of designated sites?
3) How powerful could spatially targeted mitigation be in improving outcomes for designated sites?
4) Could taking account of the relative spatial location of local NH_3 sources and SACs/SSSIs be a cost-

[1] AAE takes into account both the magnitude of the exceedance and the area exceeded.
[2] There are 536 N sensitive SACs and 4749 N sensitive SSSIs/ASSIs in the UK, with their terrestrial parts (i.e. excluding coastal waters) taking up13,820 km^2 and 19,325 km^2, respectively.

effective solution for protecting designated sites?

5) How could spatially targeted measures be implemented locally, and what might they look like?

2. Methods

2.1. UK scale assessment

For the UK scale assessment of future patterns of ammonia emissions, concentrations, deposition and Critical Loads, the suite of Defra national tools, models and datasets were used.

Agricultural ammonia *emissions* for the baseline (2008, 2020) and mitigation (2020) scenarios were calculated with the NARSES model (Webb and Misselbrook 2004, Misselbrook *et al.* 2004) and spatially distributed using the AENEID model (Dragosits *et al.* 1998, Hellsten *et al.* 2008), at a 1 km grid resolution. FAPRI (2011) projections of 2020 livestock populations and fertiliser use were used in the development of the emission scenarios. Costs of implementation of specific mitigation methods were included in the NARSES model, originally by Webb et al. (2006), but substantially updated recently by ApSimon *et al.* (2012). These datasets were then combined with the non-agricultural NH_3 emission maps from the UK National Atmospheric Emission Inventory (NAEI, www.naei.org.uk) and used as input to the UK FRAME (Fine Resolution Atmospheric Multi-pollutant Exchange) model (Fournier *et al.* 2005, Dore *et al.* 2007, Vieno *et al.* 2010, Hallsworth *et al.* 2010, Dore *et al.*, 2012), together with NO_x and SO_2 maps from the same source (version UEP43, Misra *et al.* 2012).

The FRAME model was run for all scenarios at a 1 km grid resolution, using the uncalibrated version. The model calculates annual average *gas and aerosol concentrations and deposition* for compounds of nitrogen and sulphur as well as base cations and heavy metals. For this project, the analysis focused on NH_3 concentrations and N deposition and its components (dry/wet deposition of oxidised (NO_x) and reduced N (NH_x)).

To assess the risk of environmental impacts on sensitive habitats and species by air pollutants, the critical thresholds of pollutant concentrations and deposition fluxes (CLE, CL) developed by United Nations Economic Commission for Europe (UNECE) were used. A Critical Level is the pollutant concentration in the atmosphere above which plants or ecosystems may be directly negatively affected (Nilsson and Grennfelt 1988, UBA 2004). The most recent long term critical levels for NH_3 (Cape *et al.* 2009, Sutton *et al.* 2009; UNECE 2007) are 1 µg NH_3 m^{-3} for the most sensitive ecosystems, i.e. where lichens and bryophytes are part of the ecosystem integrity, and 3 ± 1 µg NH_3 m^{-3} for higher plants in other semi-natural ecosystems. A Critical Load is a pollutant deposition below which no significant harmful effects on the environment are expected to occur according to current knowledge (Nilsson and Grennfelt 1988, UBA 2004). Nitrogen (N) CLs have been defined for specific ecosystem types (see Bobbink and Hettelingh (2011) for most up-to-date values). In contrast to the CLE approach, which is specifically defined for gases such as NH_3, the CL approach integrates all forms of reactive N and therefore requires estimates of total N deposition.

In this project, threats to sensitive habitats from atmospheric NH_3 were quantified by applying the CLEs both UK-wide and specifically to SACs and SSSIs, focusing on the 3 µg NH_3 m^{-3} threshold for scenario development, but also analysing model output for the 1 µg NH_3 m^{-3} CLE. Different indicators were used to quantify the % of designated sites exceeding a CLE (following the approach of Hallsworth *et al.* 2010, see also Figure 1):

- **Designation weighted indicator (DWI)**: shows the proportion of sites with exceedance, giving the same weight to each designated site, regardless of size. The rationale is that the designation of each site is of of equal importance, and that it is equally relevant to protect smaller nature areas in the UK countryside. The approach recognises the fact that larger SACs tend to be located in more remote (cleaner) locations, and that this indicator most closely matches to the assessment of SAC 'site integrity'.

- **Area weighted indicator (AWI)**: shows the overall area of sites with exceedance across all or part of their area, i.e. exceedance is estimated to occur in at least part of the site. The AWI implicitly assumes that the value associated with nature conservation is directly proportional to site area, while making the link to whether the integrity of each site is compromised by exceedance in any part of the site. However, for very large sites, the risk to designated features may be relatively small if only a small corner exceeds CL/CLE, and in these cases the AWI-2 may be a more suitable indicator.

- **Area weighted indicator 2 (AWI-2)**: shows the actual exceeded areas within protected sites (in km^2 and %). The AWI-2 should be treated with caution, as the designated habitats and species in any protected site may or may not be located in those areas exceeded within sites. This indicator introduces large uncertainties whether the designated features of a site would be protected or not, regardless of the % area of the site that is predicted to be below the CLE/CL. Both the DWI and the AWI, on the other hand, are more precautionary, in that a site may be considered at risk when exceedance occurs in part of its area. This indicator is included for comparitive purposes, since it matches closely to national scale mapping approaches for CLs, and potential improvements from the tested mitigation scenarios can be seen by comparing both AWI and AWI-2 between scenarios, rather than looking at them in isolation.

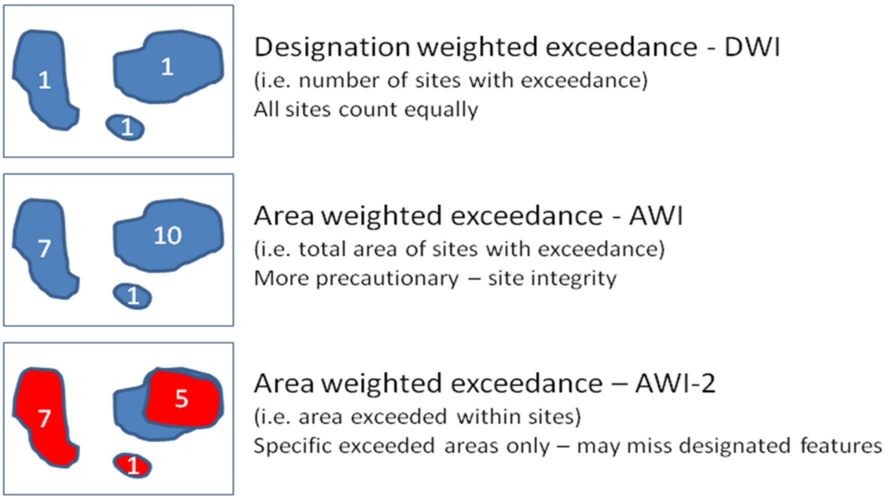


Figure 1: Graphical representation of indicators for quantifying the % of SACs/SSSIs exceeding a Critical Level (following the approach of Hallsworth et al. 2010).

The same indicators were also applied to CLE exceedance at SACs/SSSIs, but using DWI and AWI-2 only. The UK-wide CL assessment used the most recent empirical nutrient N methodology (2010 international workshop, UNECE 2010, Bobbink and Hettelingh 2011, Hall *et al*. 2011), based on observed changes in the structure or function of ecosystems. Details can be found in the most recent UK status report (Hall *et al.*, 2011: http://cldm.defra.gov.uk/Status_Reports.htm). For assessing the status of individual SACs or SSSIs, "site-relevant critical loads" (SRCL) have been developed. For nutrient N, the designated feature habitats have been related to the habitat classes for which empirical critical loads are available (Bobbink & Hettelingh, 2011; Hall *et al.*, 2011) and values at the lower, middle and upper parts of the published CL ranges. In this project, UK CL mapping values were applied. Exceedance is calculated as the amount of excess N deposition above the CL; the average accumulated exceedance (AAE) takes into account both the magnitude of the exceedance and the area exceeded.

2.2. Landscape scale assessment

For the landscape scale assessment, detailed spatial data on agricultural management and nitrogen inputs for existing study landscapes were available from previous projects (NERC GANE/LANAS, e.g., Theobald *et al.* 2004, Dragosits *et al.* 2005; NitroEurope IP, e.g. Vogt *et al.* 2013 *in press*). These landscapes represent a range of typical agricultural systems in the UK, such as arable, poultry, dairy, beef and sheep farming, interspersed with sensitive habitats. Field- and farm based emissions were calculated using the same emission factors as for the UK scale assessment, however with detailed local farm management information taken into account, such as husbandry systems, types and application rates of fertilisers and manures, housing and grazing records etc. The detailed spatial emission maps were used as input to the Local Area Dispersion and Deposition (LADD) Model (Dragosits *et al.* 2002, Theobald *et al.* 2012), together with boundary conditions from the FRAME model for the relevant mitigation scenario, to derive atmospheric NH_3 concentrations and dry deposition of reduced N (NH_x) at a 25 m grid resolution. Total N deposition, required for CL assessment, was estimated by adding the deposition of oxidised N (NO_x, dry and wet) and wet deposition of ammonium (NH_4^+) from the UK-wide 1 km FRAME model runs for different scenarios (see above for details) to the LADD dry deposition of NH_3, using appropriate land-cover specific deposition velocities (woodland vs. other semi-natural ecosystems). It is possible to combine the two different resolutions, as NH_3 dry deposition is the most spatially variable of the different components of N deposition in agricultural areas, with the other components having smoother distributions, rather than steep gradients away from sources (Vogt *et al.* 2013, in press). CLE assessment of the landscape scenarios was carried out in the same way as at the UK scale.

2.3. Mitigation measures and scenario development

Ammonia (NH_3) emission mitigation scenarios were developed using 'business as usual' projections for the year 2020 as a baseline (FAPRI, 2011), together with the latest available UK NH_3 emission inventory methodology (Misselbrook *et al.* 2011).

Mitigation measures were applied to the agricultural sector which accounts for *c.* 80% of total UK ammonia emissions. No additional mitigation options were applied to non-agricultural sources, however decreases are projected for transport emissions in particular in the business as usual scenario used in this study (e.g., due to the next generation of technology filtering through the UK vehicle fleet).

All scenarios were assessed for exceedance of NH_3 CLE2, and selected scenarios for nutrient N CLs. Critical Loads analyses were carried out both for all UK habitats and for N-sensitive SACs/SSSIs, at a 1km grid resolution:

Two main mitigation approaches are taken:

- UK-wide (uniformly distributed) application of mitigation measures
- Targeted application of measures to maximise cost-benefit for SACs/SSSIs**.**

The main mitigation scenarios consist of different sets of measures, with increasing levels of ambition. Individual measures are described below for each scenario, with further details provided in ***Appendix 1***. Table 1 summarizes the differences between the main scenarios in terms of measures applied. For all scenarios apart from the most ambitious (Mitig4) partial implementation of measures is assumed, with applicability constraints etc. taken into account. In scenario Mitig4, 100% implementation is tested, with other equally effective measures assumed to be implemented where core measures are not applicable, e.g. injection on stony ground.

The individual measures were selected from the recently published Defra Ammonia Handbook (2011), based on effectiveness and applicability, with prior implementation taken into account (more detail in ***Appendix 1***).

1. Include urease inhibitors with Urea and Urea Ammonium Nitrate fertilisers.
2. Rapid incorporation of farm yard manure (FYM) and poultry manure on arable land
3. Slurry application by low emission techniques, a) trailing shoe applicators, b) injection
4. Covering of slurry stores (floating, flexible or rigid covers)
5. Improved housing design for pigs and poultry (e.g., improved part-slatted floor designs for pigs or in-house drying systems for poultry)
6. Plastic sheeting covering all cattle and pig FYM stores
7. Storage of cattle, pig and duck FYM prior to application to land

Another scenario included in this project was mitigation by tree planting near emission sources, with an overall increase in UK woodland by 50% (Defra project AC0201, Bealey *et al*. 2013). No agricultural mitigation measures are implemented, i.e. emissions are equal to the 2020 baseline. Planting additional trees near livestock houses and manure/slurry stores to capture NH_3 can help reduce NH_3 concentration and N deposition elsewhere, provided these woodland belts are planted using the most effective design (see ***Appendix 1*** for a short summary, with full details from Defra project AC0201, Agroforestry Systems for Ammonia Abatement, final report submitted to Defra early 2013).

Table 1: Summary of measures tested in the main mitigation scenarios. More detailed descriptions of each scenario are described in the text.

Measures	LowEmSpr	Mitig1	Mitig2	Mitig3	Mitig4	Trees (AC0201)
Urease inhibitors for Urea/UAN	✓	✓	✓	✓	✓	-
Rapid manure incorporation	✓	✓	✓	✓	✓	-
Slurry application by trailing shoe	✓	✓	✓	✓	-	-
Slurry application by injection	-	-	-	-	✓	-
Covering of slurry stores	-	✓	✓	✓	✓	-
Improved housing pigs/poultry	-	✓	-	✓	✓	-
Covering of FYM stores	-	-	✓	✓	✓	-
Manure storage pre-application	-	-	✓	✓	✓	-

2.4. UK-wide vs. spatially targeted implementation of measures

All scenarios listed above were tested UK-wide, i.e. the mitigation measures were applied uniformly across the country, in addition to the selected application of scenarios over in several spatially targeted approaches, as follows (see ***Appendix 1*** for further details):

- **Application of measures inside buffer zones of different widths surrounding SACs/SSSIs**. The most ambitious scenario, Mitig4, was tested here in example buffer zone, with fixed widths of 500m, 1 km, 2 km, and 5 km around all SACs and SSSIs, respectively. In addition, variable buffer zones were assembled from these scenarios, using the minimum width required to achieve non-exceedance of the 3 µg NH_3 m^{-3} CLE. For example, SACs/SSSIs where the CLE was not exceeded in the baseline scenario were not assigned a buffer zone with associated mitigation measures. SACs/SSSIs which were exceeding the CLE without a buffer zone, but were sufficiently protected by the 500m buffer scenario, received a 500m buffer zone in this variable zone scenario, etc.
- **Application of measures inside current spatially targeted schemes, Nitrate Vulnerable Zones (NVZ)**. To investigate the effectiveness of NH_3 measures complementary with NVZ rules (i.e. measures applicable to manure storage and spreading) on SACs/SSSIs, scenario Mitig2 was applied to current UK NVZ.
- **“Maximum protectability” scenario**: building on variable buffer zones scenarios (see above), modelled agricultural emissions near SACs/SSSIs are reduced further until non-exceedance of the NH_3 Critical Level of 3 µg m^{-3} is achieved. This was modelled by reducing agricultural emissions in a 5 km radius around 1 km gridsquares still exceeding the CLE, to a level that would not exceed the CLE if no other significant non-agricultural sources or very intensive agricultural activity were present in the surrounding area (i.e. implementation of measures in the smallest possible area while achieving protection of all SACs/SSSIs).
- **Planting of trees near NH_3 emission sources** to reduce atmospheric NH_3 emissions, concentrations and N deposition while retaining 2020 baseline emission levels (linking to Defra Project AC0201, Bealey *et al.* (2013), draft final report with Defra)

3. Results & Discussion

3.1. Predicted future patterns of ammonia emissions, concentrations, deposition and effects on SACs/SSSIs 2008-2020 (business-as-usual)

To predict how ammonia emissions, concentrations, N deposition and their effects on priority habitats are likely to change towards 2020, under a ‘business as usual’ scenario, projections of livestock numbers and fertiliser use (FAPRI, 2011, Figure 2) were implemented in the NARSES inventory. This included implementation of Best Available Technologies for reducing emissions on large pig and poultry farms, which are projected to have taken place due to the implementation of Pollution Prevention and Control regulations, from 2007 onwards. Compared with 230.7 kt NH_3 in the base year 2008 (Misselbrook *et al.*, 2011), agricultural emissions in 2020 are estimated at 218.5 kt NH_3, a projected decrease of 12.2 kt or 5% (Table 2).

This small overall reduction in agricultural emissions, combined with small predicted decreases in non-agricultural emissions (mostly due to new catalytic converters gradually being adopted in the UK vehicle fleet) results in small decreases in NH_3 concentrations across the UK, on average. The predicted spatial NH_3 concentration patterns (Figure 3) show very little change (±0.1 µg m^{-3}) over most of the country, and some areas showing small decreases (light blue) in livestock emissions in rural areas and non-agricultural emissions in urban areas, contrasted by small increases (orange) in fertiliser emissions. The latter may seem counter-intuitive, however fertiliser application rates were depressed in 2008 due to economic circumstances, compared with the long-term trend (see yellow line, Figure 2). Any slightly larger changes in concentrations (>±0.5 µg m^{-3}) are due to predicted changes of some detailed source categories (agricultural or non-agricultural). As a consequence, changes to Critical Level exceedance for SACs and SSSIs are predicted to be very small. Figure 4 shows the maximum concentration in most SACs remaining more or less unchanged, with only the New Forest standing out among the larger sites as dropping below the 3 µg m^{-3} threshold (for SSSIs, see ***Appendix 2***). Overall, many sites remote from major agricultural sources (upland and mountain areas of Scotland and Wales) exceed neither of the Critical Levels (1 and 3 µg m^{-3}), whereas sites within or on the fringes of lowland agricultural areas are more at risk. Detailed statistics on numbers and areas of exceeded SACs and SSSIs are provided in the following sections.

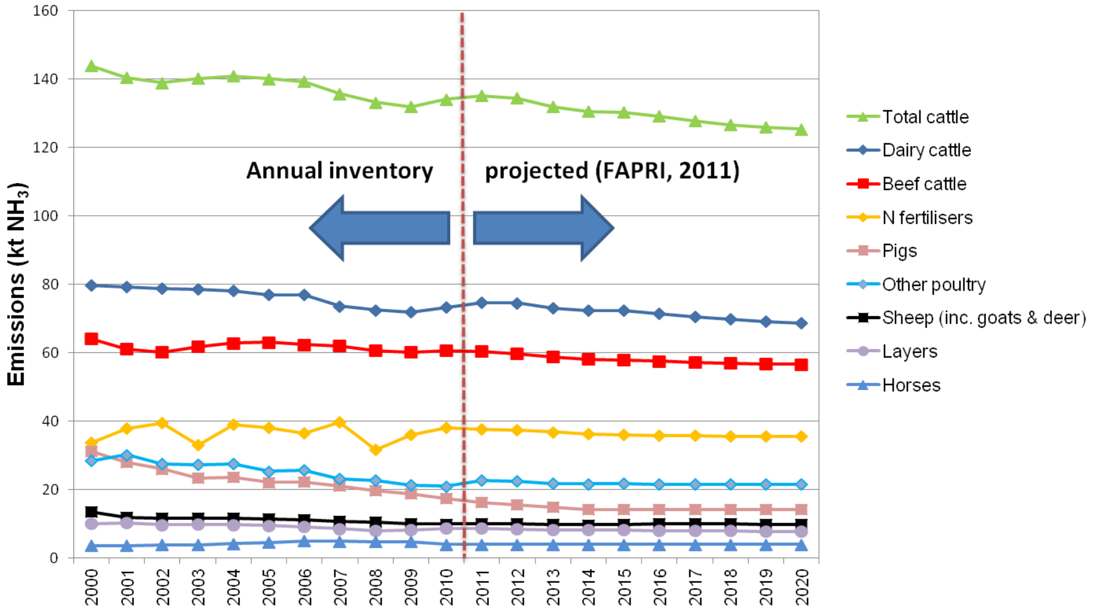


Figure 2: Trends in emissions of ammonia fom agricultural livestock and fertiliser use 2000-2020, from the UK Agricultural Emission Inventory (Misselbrook *et al.*, 2011) and FAPRI (2011) projections.

Table 2: Emissions from Agriculture (kt NH_3).for 2008 and 2020 under "business as usual" (FAPRI, 2011). Totals may not add up exactly, due to rounding.

	2008	**2020**
Dairy cattle	72.5	68.8
Beef cattle	60.7	56.6
Total cattle	**133.2**	**125.4**
Sheep (incl. goats and deer)	10.5	9.9
Pigs	19.6	14.2
Layers	8.1	7.8
Other poultry	22.8	21.7
Horses	4.7	4.0
Total livestock	**198.9**	**182.9**
N fertilisers	31.8	35.6
Total agriculture	**230.7**	**218.5**

In contrast to the predicted small changes in NH_3 emissions and concentrations, total N deposition is expected to decrease substantially, mainly due to further reduction in NO_x emissions from non-agricultural sources (transport, combustion; see Misra *et al.* (2012) for details), with the largest reduction in urban areas, as shown by the model output (see ***Appendix 2*** for maps and details of N deposition). This is expected to result in decreased exceedances of N CLs across all areas.

On a site by site basis, maximum Average Accumulated Exceedance (AAE, per feature per site) of critical load of nitrogen is predicted to improve considerably in parts of the UK (Figure 5), i.e. sites are predicted to exceed the CLs by smaller amounts than in 2008. However, the number and area of sites exceeding site-specific CLs is not expected to decrease drastically in the years to 2020. On a regional basis, Scotland's SACs are proportionally much less under threat from N deposition than the other parts of the UK (Table 3, Figure 5). It should be noted that the results from this project are based on the new (uncalibrated) 1 km FRAME model, and it is not currently possible for the 1 km deposition data to be calibrated to CBED (Smith *et al.* 2000), whereas results for previous work on Site Relevant CLs (Hall *et al*. 2006) was based on the 5km FRAME model calibrated to CBED (averaged over three years). Differences between the two projects are likely due to a) improved spatial resolution of FRAME, b) a different baseline, and c) differences between the calibrated and uncalibrated versions of FRAME.

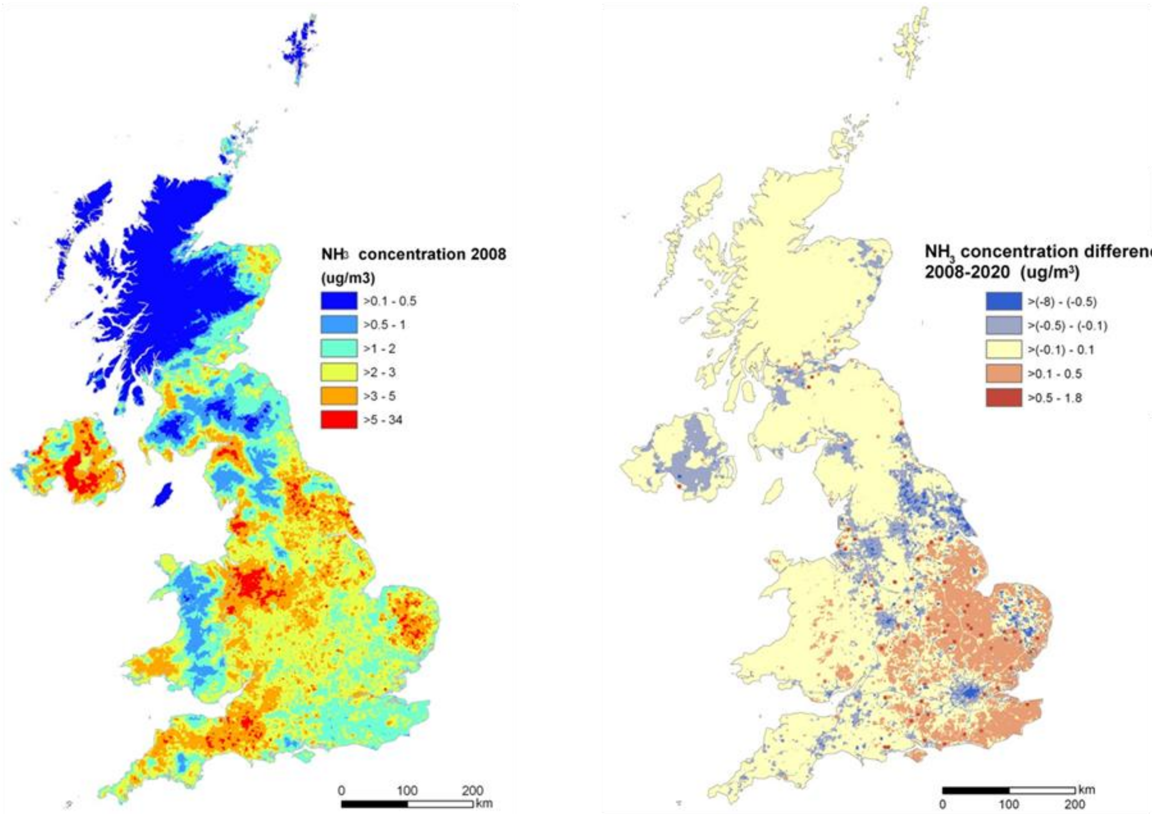


Figure 3: UK NH_3 concentrations 2008 (left) and difference 2008-2020 (right). In the difference map, blue indicates predicted decreases in concentrations, and red shows predicted increases.

Table 3: Critical Loads exceedance for SACs and SSSIs (for N sensitive habitats that have a Critical Load assigned) 2008 & 2020: Exceedances for Nutrient N based on UK mapping values.

	SACs				SSSIs			
Country	DWI 2008	DWI 2020	AWI-2 2008	AWI -2 2020	DWI 2008	DWI 2020	AWI-2 2008	AWI-2 2020
England	90.4%	84.8%	92.7%	90.9%	79.9%	74.2%	89.6%	85.1%
Wales	89.9%	88.6%	75.8%	73.8%	93.7%	89.4%	90.7%	88.6%
Scotland	30.3%	20.9%	6.3%	3.3%	33.9%	24.9%	17.4%	13.4%
Northern Ireland	94.0%	90.0%	91.3%	80.0%	77.7%	69.1%	86.4%	80.6%
United Kingdom	68.1%	61.9%	51.8%	49.1%	72.7%	66.5%	58.1%	53.9%

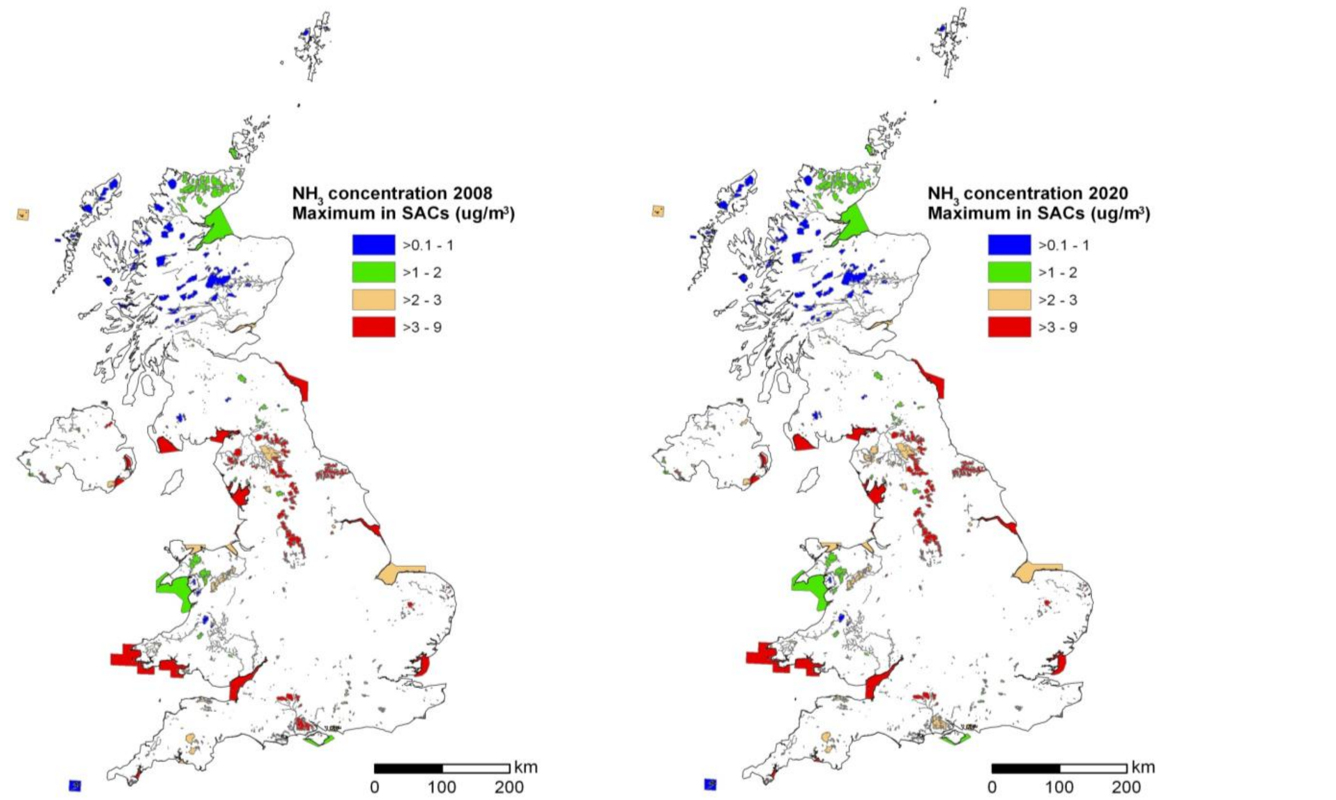


Figure 4: Maximum NH_3 concentrations in N-sensitive SACs for 2008 (left) and 2020 (right). Red shading indicates exceedance of the Critical Level of 3 µg m^{-3}, with at least some part of a site affected (DWI).

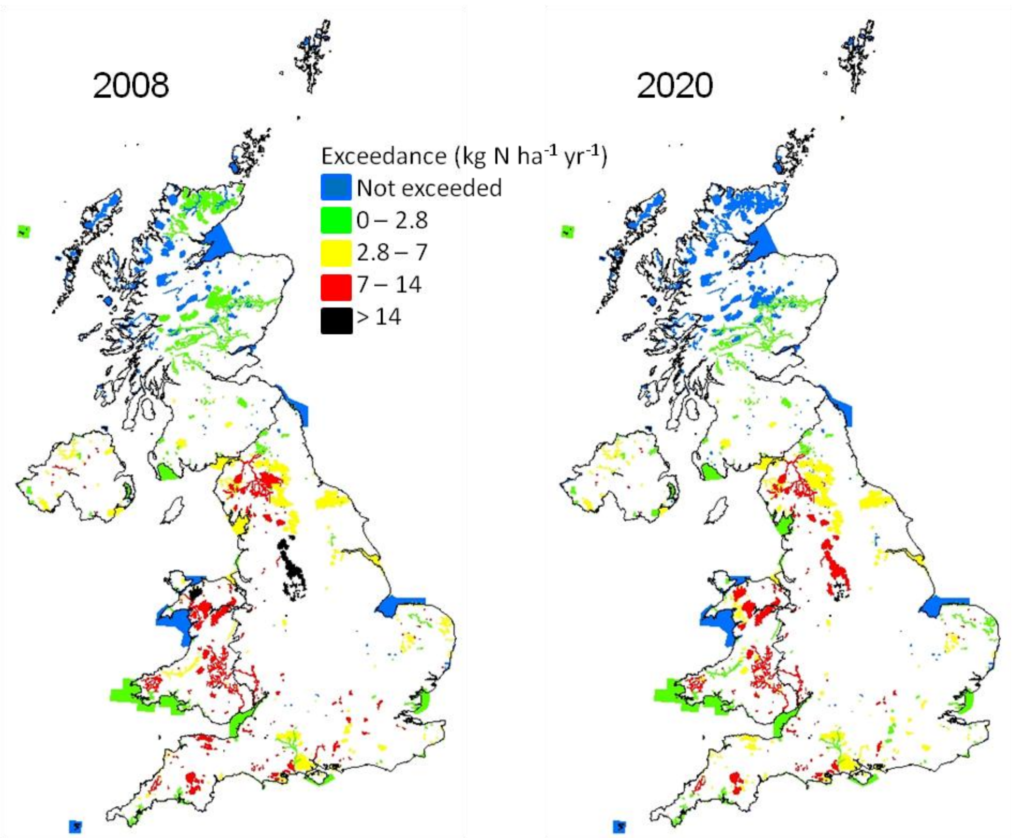


Figure 5: Maximum Average Accumulated Exceedance (AAE) (per feature per SAC) of critical load of nitrogen by FRAME 2008 and 2020 (uncalibrated) N deposition, based on the UK mapping critical load values.

3.2. Effects of UK-wide mitigation scenarios on Critical Level exceedance for SAC/SSSIs

All modelled UK-wide scenarios were compared with the 2008 and 2020 (business-as-usual) baselines, using the indicators described in Section 3.1 (DWI, AWI, AWI-2).

As expected, increased ambition in mitigation effort results in decreasing levels of exceedance of the 3µg m^{-3} Critical Level, for all indicators, for all priority habitats (SACs and SSSIs, Table 4a,b). For example, even the least ambitious scenario (use of low emission spreading techniques for fertilisers and manures, where applicable), results in a decrease of the number of SACs exceeded (DWI) from 25% to 18%, compared with the 2020 baseline. In terms of the combined area of sites no longer exceeding the Critical Level (AWI), this scenario would achieve a reduction from 32% to 24%. By comparison, the most ambitious UK-wide scenario (Mitig4) would give most protection, with only 12% (DWI) and 9% (AWI) of SACs remaining above the 3µg m^{-3} Critical Level. Differences between very similar scenarios Mitig2 and Mitig3 are relatively small, as expected. The tree planting scenario is expected to achieve similar results to the least ambitious mitigation scenario, without any technical abatement measures applied.

For the SSSIs scenarios (Table 4b), similar decreases in exceedance can be expected as for SACs. All scenarios appear to be more effective for SSSIs than for SACs. This may be due to the often larger areas of SACs (e.g. many SACs made up from combining several SSSIs) make it more difficult to achieve non-exceedance using the more precautionary indicators (DWI, AWI). The AWI-2, on the other hand, is slightly higher for SSSIs than SACs, i.e. showing a slightly smaller effectiveness of the measures, perhaps related to the small SSSIs often located in intensive lowland areas.

Additional data for UK-wide coverage across the land surface area are shown in Table 1 of ***Appendix 3***.

Table 4a: Total and percentage exceedance of the 3µg m^{-3} NH_3 Critical Level in UK SACs. Using the Designation weighted indicator (DWI), Area weighted indicator (AWI), and Area-weighted indicator-2 (AWI-2).

	DWI (no. of SACs)	DWI (%)	AWI (km^2)	AWI (%)	AWI-2 (km^2)	AWI-2 (%)
Base 2008	136	25%	4,992	36%	184	1.3%
Base 2020	133	25%	4,435	32%	184	1.3%
Woodland	92	17%	3,952	29%	107	0.8%
LwEmSpr	95	18%	3,270	24%	110	0.8%
Mitig1	87	16%	3,190	23%	104	0.8%
Mitig2	80	15%	2,376	17%	92	0.7%
Mitig3	78	15%	2,370	17%	86	0.6%
Mitig4	64	12%	1,244	9%	62	0.4%
Mitig2 NVZs	109	20%	4,120	30%	141	1.0%
Mitig4 500 m	113	21%	3,847	28%	139	1.0%
Mitig4 1 km	97	18%	3,676	27%	122	0.9%
Mitig4 2 km	87	16%	3,016	22%	104	0.8%
Mitig4 5 km	76	14%	1,957	14%	81	0.6%
Mitig4 variable buffer	79	15%	2,999	22%	84	0.6%
Mitig4 protectability	13	2%	353	3%	20	0.1%

Table 4b: Total and percentage exceedance of the 3µg m^{-3} NH_3 Critical Level in UK SSSIs. Using the Designation weighted indicator (DWI), Area weighted indicator (AWI), and Area-weighted indicator-2 (AWI-2).

	DWI (no. of SSSIs)	DWI (%)	AWI (km2)	AWI (%)	AWI-2 (km2)	AWI-2 (%)
Base 2008	1,073	23%	4,050	21%	536	2.8%
Base 2020	1,070	23%	3,590	19%	538	2.8%
Woodland	715	15%	2,461	13%	307	1.6%
LwEmSpr	684	14%	1,916	10%	307	1.6%
Mitig1	655	14%	1,871	10%	287	1.5%
Mitig2	611	13%	1,800	9%	257	1.3%
Mitig3	590	12%	1,783	9%	245	1.3%
Mitig4	454	10%	1,527	8%	176	0.9%
Mitig2 NVZs	775	16%	2,905	15%	368	1.9%
Mitig4 500 m	891	19%	3,109	16%	397	2.1%
Mitig4 1 km	766	16%	2,404	12%	341	1.8%
Mitig4 2 km	637	13%	1,805	9%	277	1.4%
Mitig4 5 km	503	11%	1,583	8%	201	1.0%
Mitig4 variable buffer	548	12%	1,672	9%	223	1.2%
Mitig4 protectability	69	1%	452	2%	33	0.2%

The majority of UK SACs, exceed the 1µg m^{-3} Critical Level set for the most sensitive species (Table 5a). It is evident that the lower ambition scenarios (up to Mitig3 shown here) are very ineffective at improving protection for these species, with only the most ambitious scenario (Mitig4), applied UK-wide, starting to reduce exceedances of the 1µg m^{-3} Critical Level substantially, using the AWI. For SSSIs (Table 5b), even Mitig4 UK-wide is not expected to make a substantial difference to the exceedance of the 1µg m^{-3} Critical Level.

Table 5a: Proportion of SACs exceeding the 1µg m^{-3} Critical Level for the most sensitive species, using three different indicators.

	DWI (no. of SACs)	DWI (%)	AWI (km^2)	AWI (%)	AWI-2 (km^2)	AWI-2 (%)
Base 2008	394	73.5%	9,498	68.7%	4,696	34.0%
Base 2020	397	74.1%	9,537	69.0%	4,864	35.2%
Woodland	391	72.9%	9,525	68.9%	4,423	32.0%
LwEmSpr	387	72.2%	9,483	68.6%	4,172	30.2%
Mitig1	387	72.2%	9,483	68.6%	4,111	29.7%
Mitig2	383	71.5%	9,476	68.6%	3,994	28.9%
Mitig3	381	71.1%	9,442	68.3%	4,218	30.5%
Mitig4	377	70.3%	7,999	57.9%	3,481	25.2%
Mitig2 NVZs	392	73.1%	9,490	68.7%	4,484	32.5%
Mitig4 500 m	391	72.9%	9,490	68.7%	4,610	33.4%
Mitig4 1 km	390	72.8%	9,485	68.6%	4,500	32.6%
Mitig4 2 km	386	72.0%	9,478	68.6%	4,341	31.4%
Mitig4 5 km	382	71.3%	9,442	68.3%	4,066	29.4%
Mitig4 variable buffer	392	73.1%	9,527	68.9%	4,350	31.5%
Mitig4 protectability	392	73.1%	9,527	68.9%	4,218	30.5%

Table 5b: Proportion of SSSIs exceeding the 1μg m^{-3} Critical Level for the most sensitive species, using three different indicators.

	DWI (no. of SSSIs)	DWI (%)	AWI (km^2)	AWI (%)	AWI-2 (km^2)	AWI-2 (%)
Base 2008	2934	81.5%	15,214	78.7%	7,712	39.9%
Base 2020	2946	81.8%	15,255	78.9%	7,941	41.1%
Woodland	2912	80.8%	15,136	78.3%	6,907	35.7%
LwEmSpr	2886	80.1%	15,013	77.7%	7,064	36.6%
Mitig1	2880	80.0%	15,009	77.7%	6,979	36.1%
Mitig2	2856	79.3%	14,945	77.3%	6,818	35.3%
Mitig3	2844	79.0%	14,917	77.2%	6,720	34.8%
Mitig4	2794	77.6%	14,710	76.1%	6,151	31.8%
Mitig2 NVZs	2917	81.0%	15,137	78.3%	7,464	38.6%
Mitig4 500 m	2919	81.0%	15,144	78.4%	7,563	39.1%
Mitig4 1 km	2897	80.4%	15,064	78.0%	7,363	38.1%
Mitig4 2 km	2863	79.5%	14,946	77.3%	7,063	36.6%
Mitig4 5 km	2819	78.3%	14,860	76.9%	6,489	33.6%
Mitig4 variable buffer	2924	81.2%	15,190	78.6%	7,292	37.7%
Mitig4 protectability	2905	80.6%	15,082	78.0%	6,907	35.7%

3.3. Effects of spatially targeted mitigation scenarios on Critical Level exceedance for SAC/SSSIs

All spatially targeted scenarios were compared with the 2008 and 2020 (business-as-usual) baselines, in the same way as for the UK-wide scenarios, using the DWI, AWI and AWI-2 indicators for effects on SACs/SSSIs as described in Section 3.1. The scenarios were also assessed for exceedance of the 1 and 3 μg m^{-3} Critical Levels across the UK land surface area (please see ***Appendix 3*** for an additional table).

Application of mitigation measures (Mitig4) in concentric buffer zones (500m – 5 km) around sites is shown to increase both the numbers and areas of sites protected with increasing widths of buffer zones (Table 4). Variable size buffer zones, designed at a minimum width needed to achieve concentrations <3 μg m^{-3} (up to a maximum width of 5 km) provide a similar effect as 2 km-5 km zones (depending on the indicator), with UK-wide emission reductions under this scenario being similar to buffer zones of average 2 km width (Table 4). **The larger single-width (e.g., 2 km buffer zones around all SACs/SSSIs) and the variable buffer zones (buffer zone width tailored to site) are almost as effective as the UK-wide Mitig4 scenario, indicating that targeting measures in the vicinity of priority habitats is an effective way of maximising benefits while minimising costs.** Spatially targeting measures complementary for NVZs (Mitig2) across all current UK NVZs, on the other hand, is less effective compared with other spatially targeted scenarios. This is mainly due to a lack of spatial overlap of SACs/SSSIs with NVZs (apart from Northern Ireland, which is 100% designated NVZ).

A comparison of the maximum NH_3 concentrations at SACs is shown in Figure 5 for the 2020 baseline, the most ambitious scenario (Mitig4) UK-wide and using the optimised (variable) buffer zones, respectively. Despite large differences in the overall emission reductions required from the 2020 baseline (Table 6[3]), -27% for the UK-wide application and only -6% for the variable SAC buffer zones (or 10% for SSSIs), the resulting NH_3 concentrations are very similar for both scenarios (Figure 6, see also Table 4 above for % reduction in indicators. Due to space limitations in the main report, the equivalent SSSI maps are provided in Figure 1 of ***Appendix 3****,* together with further details, such as results on AWI-2 in Table 2 of ***Appendix 3***).

The "maximum protectability" scenarios for SACs and SSSIs resulted in very small numbers of sites where it was not possible to achieve concentrations below the CLE of 3 μg m^{-3}, by targeting local sources too large for the modest reductions from the applied mitigation measures to have sufficient effect (Figure 7). It should be noted that this scenario is not realistic for implementation, especially at the UK scale, but does provide an indication whether tough local mitigation measures using local planning approaches would theoretically be able to resolve exceedances. In practice this shows a high potential for local measures to avoid concentrations above 3 μg NH_3 m^{-3} in the UK. The exceedances at the remaining "non-protectable" sites are due to either large non-agricultural emission sources in the vicinity, or a very high density of emission sources (agricultural and non-agricultural) over a larger surrounding area not allowing concentrations to deplete sufficiently before they reach the site.

[3] For space saving reasons, this table also contains cost estimates, which are discussed in a later section.

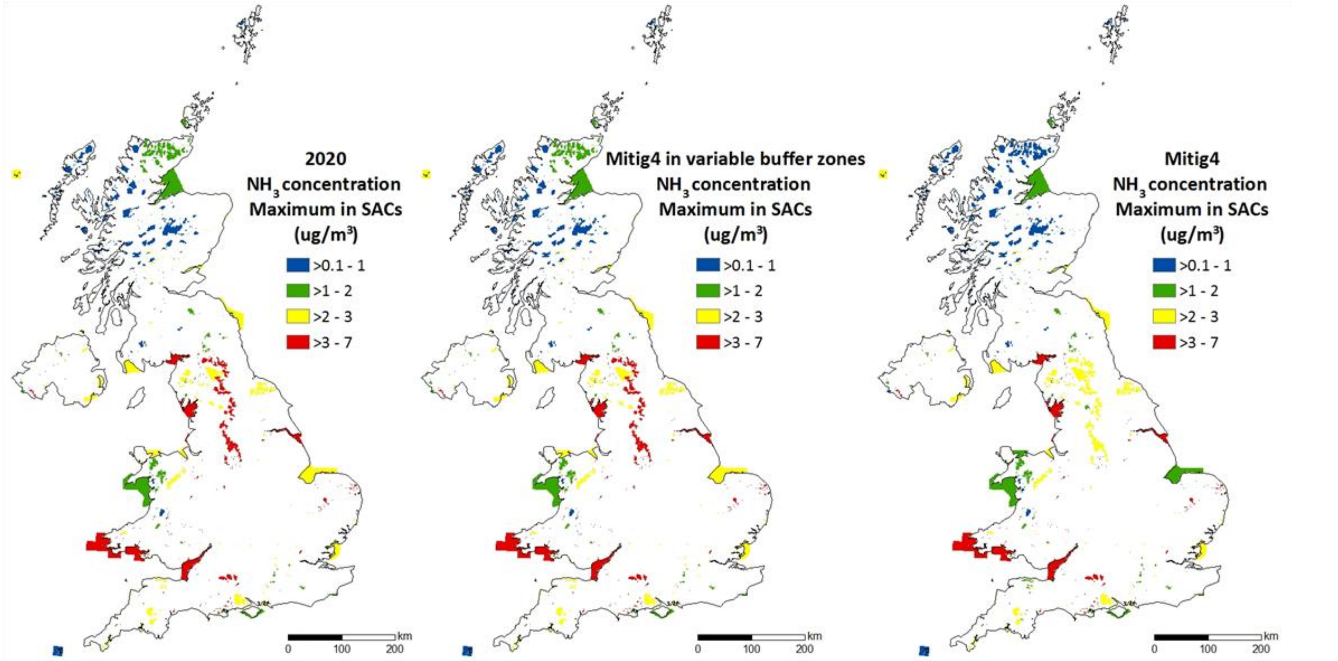
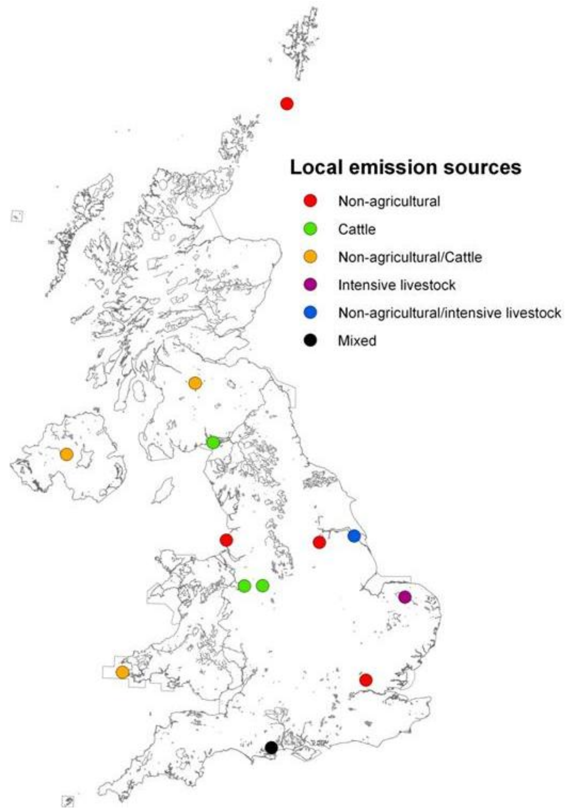


Figure 6: Effects of scenario Mitig4 on 3 µg m^{-3} Critical Level exceedance in SACs: Maximum NH_3 concentrations in SACs for the 2020 Baseline (left), UK-wide application of Mitig4 (middle) and tailored variable buffer zones around SACs with application of Mitig4 (right).



SACs not protected

SITENAME	Max. NH_3 concentration (µg m^{-3})
Brown Moss	3.0518
Clyde Valley Woods	3.7660
Dorset Heaths	5.0078
Epping Forest	4.0719
Fair Isle	3.1124
Hatfield Moor	4.1330
Humber Estuary	4.3256
Pembrokeshire Marine / Sir Ben	6.8527
River Wensum	4.6720
Sefton Coast	3.8848
Solway Firth	3.2558
Upper Ballinderry River	3.1282
West Midlands Mosses	3.9272

Figure 7: "Protectability" scenario of CLE exceedance for SACs: Site not protectable with measures applied (variable buffer zones around SACs (Mitig4) and additional reductions in agricultural emissions in areas surrounding exceeded parts of SACs. The colour scheme shows the primary emission sources responsible for the continued exceedance of the affected sites. The adjacent table shows the maximum NH_3 concentration estimated for the sites after application of the measures.

By contrast, none of the spatially targeted scenarios discussed above are very effective at reducing the exceedance of the 1µg m^{-3} Critical Level. This is not really surprising, as the spatially targeted zones were designed to reduce exceedances of the 3 µg m^{-3} Critical Level, rather than aim for the 1µg m^{-3} Critical Level. For buffer zones to be effective at the 1µg m^{-3} Critical Level, a combination of wider buffer zones and stricter measures would be required for large parts of the UK, with the exception of Scotland, where many sites appear sufficiently protected already.

Table 6: Assessment of effectiveness and cost-effectiveness of UK-wide and spatially targeted mitigation scenarios for NH_3 Critical Level exceedance (3 μg m^{-3}), separately for SACs (top) and SSSIs (bottom). Additional data for AWI-2 are shown in Table 2 of ***Appendix 3***.

Scenario name	Total agric. emission (kt NH_3)	% emission reduction from 2020 baseline	Additional SAC sites protected (c.f. 2020)	Additonal SAC area protected km^2 (c.f. 2020)	% Additional SAC sites protected (c.f. 2020)	% Additonal SAC area protected km^2 (c.f. 2020)	Cost £M (inc. baseline cost)	Cost £M (exc. baseline cost)	% additional SACs protected / £5M	% additonal SAC area protected / £5 M
Baseline2020	218.5	-	-	-	0%	0%	19.8	0.0	-	-
UK - LowEmSpreading	186.8	15%	38	1,165	29%	26%	57.1	37.3	4%	4%
UK - Mitig1	184.2	16%	46	1,245	35%	28%	71.8	52.0	3%	3%
UK - Mitig2	179.1	18%	53	2,059	40%	46%	82.5	62.7	3%	4%
UK - Mitig3	177.1	19%	55	2,065	41%	47%	100.5	80.7	3%	3%
UK - Mitig4	160.6	26%	69	3,191	52%	72%	104.5	84.7	3%	4%
Current NVZ-Mitig2	193.6	11%	24	315	18%	7%	59.5	39.7	2%	1%
Buffers Mitig4 500 m	215.8	1%	20	588	15%	13%	23.9	4.1	18%	16%
Buffers Mitig4 1km	213.6	2%	36	759	27%	17%	27.1	7.3	19%	12%
Buffers Mitig4 2 km	209.2	4%	46	1,419	35%	32%	33.5	13.7	13%	12%
Buffers Mitig4 5 km	197.6	10%	57	2,478	43%	56%	50.5	30.7	7%	9%
Buffers Mitig4 variable	205.9	6%	54	1,436	41%	32%	38.2	18.4	11%	9%
Max protectability	199.9	9%	120	4,082	83%	92%	-	-	n/a	n/a
Additional Trees	218.5	0%	41	483	31%	11%	-	-	n/a	n/a

Scenario name	Total agric. emission (kt NH_3)	% emission reduction from 2020 baseline	Additional SSSI sites protected (c.f. 2020)	Additonal SSSI area protected km^2 (c.f. 2020)	% Additional SSSI sites protected (c.f. 2020)	% Additonal SSSI area protected km^2 (c.f. 2020)	Cost £M (inc. baseline cost)	Cost £M (exc. baseline cost)	% additional SSSIs protected / £5M	% additonal SSSI area protected / £5
Baseline2020	218.5	-	-	-	-	-	19.8	0.0	-	-
UK - LowEmSpreading	186.8	15%	386	1,674	36%	47%	57.1	37.3	5%	6%
UK - Mitig1	184.2	16%	415	1,719	39%	48%	71.8	52.0	4%	5%
UK - Mitig2	179.1	18%	459	1,790	43%	50%	82.5	62.7	3%	4%
UK - Mitig3	177.1	19%	480	1,807	45%	50%	100.5	80.7	3%	3%
UK - Mitig4	160.6	26%	616	2,063	58%	57%	104.5	84.7	3%	3%
Current NVZ-Mitig2	193.6	11%	295	685	28%	19%	59.5	39.7	3%	2%
Buffers Mitig4 500 m	213.4	2%	179	481	17%	13%	23.9	4.1	21%	16%
Buffers Mitig4 1km	208.4	5%	304	1,186	28%	33%	27.1	7.3	20%	23%
Buffers Mitig4 2 km	197.4	10%	433	1,785	40%	50%	33.5	13.7	15%	18%
Buffers Mitig4 5 km	173.5	21%	567	2,007	53%	56%	50.5	30.7	9%	9%
Buffers Mitig4 variable	197.1	10%	522	1,918	49%	53%	38.2	18.4	13%	14%
Max protectability	181.6	17%	1001	3,138	94%	87%	-	-	n/a	n/a
Additional Trees	218.5	0%	355	1,128	33%	31%	-	-	n/a	n/a

3.4. Effects of UK-wide and spatially targeted mitigation scenarios on Critical Loads exceedance for SAC/SSSIs

The CL exceedance results for the 2020 baseline scenario and three of the mitigation scenarios are summarised by country in the tables below. The areas exceeded are lowest for all scenarios in Scotland reflecting the lower nitrogen deposition to this region (Table 7). The largest areas exceeded are across England, with the highest exceedances in the Pennines, Cumbria, and Dartmoor; and across Wales, with the highest exceedances in the upland areas of north and mid Wales, and in the valleys in south Wales (see ***Appendix 4*** for figures and additional details). The spatial patterns of exceedances are similar for all scenarios. As expected, the most ambitious UK-wide mitigation scenario (Mitig4) gives the smallest areas of exceedance of all scenarios for all countries, with the total area exceeded 6% lower than the 2020 baseline, and the AAE 0.6 kg N ha^{-1} $year^{-1}$ lower than the 2020 baseline (Table 7). There is little difference in the critical load exceedance results for the other two mitigation scenarios (Scenario Mitig4 applied in variable buffer zones around SACs and SSSIs, respectively, see main report and ***Appendix 1*** for details).

Table 7: Summary of the nitrogen critical load exceedance results for UK habitat areas sensitive to eutrophication, for the 2020 baseline scenario and three mitigation scenarios for 2020.

Country	Percentage habitat area exceeding critical loads and (in brackets) the AAE (kg N ha^{-1} $year^{-1}$)			
	2020 baseline	Mitig4 (UK-wide)	Variable size targeted buffer zones around SACs	Variable size targeted buffer zones around SSSIs
England	78.1 (4.41)	66.5 (2.81)	75.3 (3.98)	73.8 (3.67)
Wales	84.3 (4.29)	76.8 (3.05)	82.1 (3.83)	81.6 (3.74)
Scotland	4.8 (0.09)	2.3 (0.03)	4.4 (0.08)	4.1 (0.07)
Northern Ireland	46.7 (2.03)	30.8 (1.03)	41.4 (1.75)	39.7 (1.56)
UK	33.8 (1.73)	27.8 (1.11)	32.4 (1.55)	31.7 (1.45)

Spatially targeted mitigation measures are most effective for reducing NH_3 concentration in the vicinity of sources and hence the SACs/SSSIs they are close to, due to the spatially variable nature of NH_3 concentrations associated with its ground level sources in the rural environment.

Targeting Critical Loads exceedance through such measures can make a contribution, but with quantitatively smaller results for a number of reasons. Firstly, the component of total N deposition that can be targeted most effectively by measures near SACs/SSSIs is dry deposition of reduced N (mostly consisting of NH_3), due to the high deposition velocity, particularly for forest and other seminatural ecosystems, as these vegetation types have low canopy resistance for NH_3 dry deposition. By contrast, wet N deposition (both oxidised and reduced) is caused primarily by the washout of aerosol particles from the atmosphere which are associated with long range transport. This component of N deposition can not be reduced by local abatement measures. As NH_3 is a soluble gas, however, some reduction in NH_x wet deposition can be expected by local abatement of NH_3 emissions. Finally, approx. 50% of the total UK N deposition is due to oxidised N (NO_x) (RoTAP, 2012), which cannot be targeted with NH_3 measures.

Therefore, in areas dominated by or with substantial N deposition originating from NO_x (dry or wet) or wet deposition of NH_x, measures targeted at reducing NH_3 emissions will only tackle part of the overall N load. For SACs/SSSIs located in such areas, only substantial overall reductions in N emissions across the country (and internationally) will enable significant reductions in exceedance of Critical Loads.

Nevertheless, SACs/SSSIs located in intensive lowland agricultural regions with substantial dry deposition of NH_3, will benefit from spatially targeted measures, as can be seen in Figure 8 showing Maximum Average Accumulated Exceedance (AAE) for SACs for the 2020 baseline and the variable SAC buffer zone scenarios (for SSSI details and more detailed tabulated results see ***Appendix 4)***. In particular, sites in the Eden Valley, the Hampshire Avon and East Anglia, to name a few, show reductions in the magnitude of exceedance.

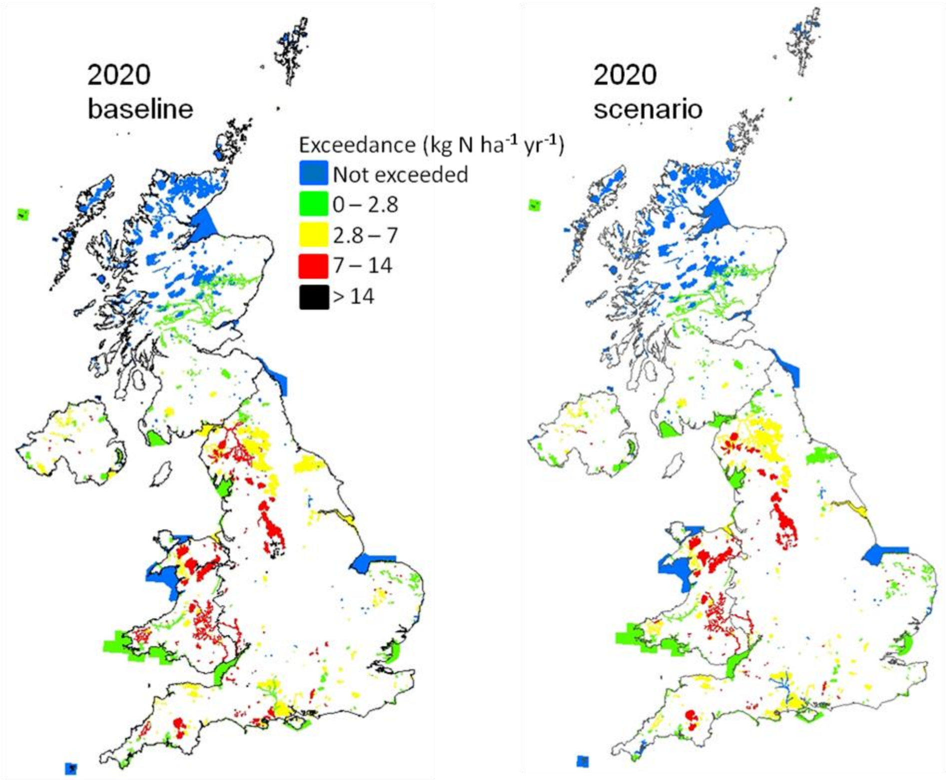


Figure 8: Maximum Average Accumulated Exceedance (AAE) (per feature per SAC) of critical load of nitrogen by FRAME (uncalibrated) 2020 baseline (left) and 2020 Scenario variable buffer zones around SACs, based on the UK mapping critical load values.

3.5. Differences in the exceedance of Critical Levels between UK countries (UK-wide and spatially targeted scenarios for SACs and SSSIs)

From the maps presented so far, it is evident that there are distinct spatial patterns across the regions of the UK, with SACs and SSSIs in some areas much more at risk from Critical Level and Critical Loads exceedance than others. In addition to the UK-wide assessment presented so far, the NH_3 Critical Level statistics were also analysed at a country basis, separately for England, Wales, Scotland and Northern Ireland (Table 7). In the following paragraphs, the results are discussed for SACs first, for both UK-wide mitigation scenarios and spatially targets scenarios in turn, followed by the same analyses for SSSIs.

3 µg m^{-3} Critical Level

For ***SACs*** in the 2020 baseline scenario, exceedances of the 3 µg m^{-3} CLE are largest in England, for both the precautionary indicators, Designation (DWI) and Area weighted (AWI), at 38% and 67%. Exceedance levels in Northern Ireland are similarly high, at 34% (DWI) and 51% (AWI). In Scotland, by contrast, only 3.5% of sites exceed the 3 µg m^{-3} CLE by designation and 0.8% by area, with Wales at approx. 20% (DWI) and 19% (AWI). This closely reflects the spatial variability of NH_3 concentrations across the UK (Figure 3, left, with very small predicted changes towards 2020).

The **UK-wide mitigation scenarios** for England show increasing effectivess with increasing ambitions, as for the UK-wide statistics, whereas the interpretation of the Welsh and Scottish data is less straightforward. This is mainly due to the relatively small absolute number of sites exceeding the 3 µg m^{-3} CLE in both countries, and the associated influence of individual sites (DWI) or larger sites (AWI) dropping below 3 µg m^{-3} is more noticeable.

For sites exceeding the 3 µg m^{-3} CLE in the 2020 baseline scenario, UK-wide mitigation measures appear quite successful in all countries, with the proportion of sites exceeded reducing dramatically under Mitig4, by approx. 50% of sites (DWI) compared with the 2020 baseline, for all four countries. Even higher proportions exceed the 3 µg m^{-3} CLE for the AWI for all countries, apart from Wales. In England, for example, the proportion of exceeded sites (DWI) decrease from 38% in the 2020 baseline scenario to 17% under Mitig4, and the AWI from 67% to 14%. Planting additional trees, while estimated to be similarly effective as the least ambitious UK-wide mitigation scenarios across the UK, appears to be a particularly suitable measure in Northern Ireland with regard to the DWI. A possible reason for this is the very small current proportion of woodland cover in Northern Ireland, compared with the rest of the UK.

For the **spatially targeted scenarios** at SACs (Table 8), a few interesting differences between the countries can be seen: the English data are very similar to the UK-wide data described in Section 3.3 above, as the UK-wide statistics are dominated by the large number of English sites exceeding the 3 µg m^{-3} CLE. In Wales and Scotland, the small absolute numbers of sites included in the statistics again show the influence of individual sites, with very little difference between some of the scenarios. Despite the small number of exceeded sites, it could be suggested that in Scotland, where NH_3 concentrations are low over large parts of the country, all buffer zone scenarios may be successful measures from an AWI perspective, with most larger sites only requiring measures in the immediate vicinity, to make a substantial % difference.

In Northern Ireland, the NVZ scenario (Mitig2) appears be very successful, compared with the other countries. However this is due to the entire country being designated as a NVZ, with similar improvements achieved as for Mitig2 UK-wide. Also, all buffer zones > 1 km appear to be equally effective as each other in Northern Ireland from an AWI perspective, with virtually no difference between the Mitig4 UK-wide and the 2 km, 5km and variable buffer zones. The reason for this anomaly appears to be in the size distribution and concentration pattern of exceeded sites in Northern Ireland, with several individual small SACs requiring the slightly larger buffer zones, whereas smaller buffer zones of <2 km are sufficient for the larger SACs.

For ***SSSIs***, the overall patterns for both UK-wide and spatially targeted scenarios are similar to those for SACs, apart from Northern Ireland showing consistently much larger exceedances than England, for both the AWI and DWI. For **UK-wide scenarios**, the largest differences can again be found for the most ambitious scenario (Mitig4), whereas the less ambitous scenarios appear to be almost interchangeable for Wales, Scotland and Northern Ireland. This may be explained by more intensive agriculture being present in the vicinity of most SSSIs in England, with larger overall mitigation efforts required to push sites below 3µg NH_3 m^{-3}.

For the scenarios **spatially targeted** at SSSIs, the largest differences between the different buffer zone widths can be seen in England, for both DWI and AWI, which appear relatively efficient, compared with the UK-wide Mitig4 scenario. For SSSIs in England, the scenario targeting current NVZs (Mitig2) is much more effective than for SACs, especially for the DWI, due to a relatively larger number of small SSSIs embedded in the intensive agricultural lowland areas designated as NVZs, compared with SACs.

For Northern Irish ASSIs, it appears that achieving concentrations below 3 µg m^{-3} is relatively more difficult than in other parts of the UK, even with a full UK-wide implementation of the most ambitious scenario (Mitig4). This is likely due to the relatively constant/even distribution of medium/high concentrations from cattle farming across most of the province, compared with the more variable overall concentration patterns across the rest of the UK (Figure 3 (left), concentration map).

Overall, SACs appear to be easier to protect than SSSIs/ASSIs in Scotland and Northern Ireland, whereas the opposite is the case for England and Wales. For SACs in England and Northern Ireland, the DWI is larger than the AWI, whereas in Scotland and Wales the AWI is larger than the DWI. This may be due to some large SACs (that are exceeding with less ambitious mitigation measures) due to a sizeable emission source (or sources) that would require bigger efforts.

Table 8: UK-wide and spatially target mitigation scenarios: Percentage of ammonia critical level exceedance (>3 µg m^{-3}) in SACs (top table) and SSSIs (bottom table) by UK country (England, Wales, Scotland, Northern Ireland). Indicators shown are the DWI (by designation) and AWI (by area).

SACs 3 µg m^{-3}	England			Wales			Scotland			Northern Ireland		
	DWI	AWI	AWI-2	DWI	AWI	AWI-2	DWI	AWI	AWI-2	DWI	AWI	AWI-2
Base 2008	39%	77%	1.9%	18%	19%	1.1%	3%	0.8%	0.08%	39%	60%	5.1%
Base 2020	38%	67%	2.0%	20%	19%	1.2%	3%	0.8%	0.07%	34%	51%	4.3%
Woodland	26%	63%	1.2%	11%	17%	0.7%	2%	0.3%	0.05%	25%	15%	2.2%
LwEmSpr	26%	47%	1.2%	11%	17%	0.7%	2%	0.3%	0.05%	29%	44%	2.5%
Mitig1	23%	46%	1.2%	11%	17%	0.7%	2%	0.3%	0.05%	27%	43%	2.3%
Mitig2	21%	34%	1.0%	11%	17%	0.6%	2%	0.3%	0.05%	24%	15%	1.9%
Mitig3	21%	34%	1.0%	11%	17%	0.6%	2%	0.2%	0.05%	23%	15%	1.7%
Mitg4	17%	14%	0.7%	9%	15%	0.3%	1%	0.2%	0.04%	19%	14%	1.0%
Mitig2 NVZs	30%	65%	1.5%	20%	19%	1.2%	3%	0.8%	0.07%	24%	15%	1.9%
Mitig4 500m	30%	57%	1.5%	16%	18%	0.9%	3%	0.3%	0.06%	34%	51%	3.4%
Mitig4 1km	27%	55%	1.3%	13%	18%	0.8%	2%	0.3%	0.05%	29%	44%	3.0%
Mitig4 2km	24%	47%	1.2%	10%	16%	0.6%	2%	0.3%	0.05%	27%	15%	2.5%
Mitig4 5km	21%	27%	1.0%	9%	15%	0.4%	2%	0.3%	0.05%	23%	15%	1.8%
Mitig4 variable buffer	22%	46%	1.0%	10%	16%	0.4%	2%	0.3%	0.05%	23%	15%	1.9%
Mitig4 protectability	4%	3%	0.3%	1%	9%	0.1%	1%	0.2%	0.04%	1%	0%	0.0%

SSSIs 3 µg m^{-3}	England			Wales			Scotland			Northern Ireland		
	DWI	AWI	AWI-2	DWI	AWI	AWI-2	DWI	AWI	AWI-2	DWI	AWI	AWI-2
Base 2008	30%	40%	5%	11%	6%	2%	4%	1.8%	0.3%	48%	65%	11%
Base 2020	29%	35%	5%	13%	6%	2%	4%	1.7%	0.3%	44%	59%	10%
Woodland	20%	23%	3%	6%	4%	1%	3%	1.2%	0.2%	29%	51%	4%
LwEmSpr	19%	16%	3%	6%	4%	1%	3%	1.2%	0.2%	32%	53%	5%
Mitig1	18%	15%	3%	6%	4%	1%	3%	1.2%	0.2%	31%	53%	4%
Mitig2	17%	14%	2%	6%	4%	1%	3%	1.2%	0.1%	28%	51%	4%
Mitig3	16%	14%	2%	6%	4%	1%	2%	1.2%	0.1%	27%	51%	3%
Mitg4	12%	11%	2%	4%	4%	1%	2%	1.1%	0.1%	22%	50%	2%
Mitig2 NVZs	21%	27%	3%	12%	6%	2%	4%	1.7%	0.3%	27%	50%	4%
Mitig4 500m	25%	29%	3%	9%	6%	2%	3%	1.7%	0.2%	37%	58%	8%
Mitig4 1km	21%	21%	3%	7%	4%	1%	3%	1.2%	0.2%	33%	55%	7%
Mitig4 2km	18%	14%	2%	6%	4%	1%	3%	1.2%	0.1%	28%	50%	5%
Mitig4 5km	14%	12%	2%	4%	4%	1%	2%	1.1%	0.1%	25%	50%	3%
Mitig4 variable buffer	15%	13%	2%	5%	4%	1%	2%	1.1%	0.1%	25%	50%	3%
Mitig4 protectability	2%	5%	0%	0%	0%	0%	1%	0.9%	0.0%	3%	0%	0%

1 µg m^{-3} Critical Level

Almost all (>90%) SACs and SSSIs exceed the 1 µg m^{-3} CLE set for the most sensitive species in England, Wales and Northern Ireland for the DWI and AWI, whereas the much lower NH_3 concentrations in Scotland result in a very different picture, with numbers in the range of 17-46% (Table 9). As expected, the % area exceeded is substantially lower for the AWI-2, with the exception of Northern Ireland, where both SACs and SSSIs are still estimated at >90%. Similar to the UK-wide assessment of exceedance of the 1 µg m^{-3} CLE (Section 3.2), the lower-ambition mitigation scenarios do not result in large reductions of exceedance, with the main substantial changes achieved with UK-wide measures.

Table 9: UK-wide and spatially target mitigation scenarios: Percentage of ammonia critical level exceedance (>1 µg m^{-3}) in SACs (top table) and SSSIs (bottom table) by UK country (England, Wales, Scotland, Northern Ireland). Indicators shown are the DWI (by designation) and AWI (by area).

SACs 1 µg m^{-3}	England			Wales			Scotland			Northern Ireland		
	DWI	AWI	AWI-2	DWI	AWI	AWI-2	DWI	AWI	AWI-2	DWI	AWI	AWI-2
Base 2008	99%	99%	62%	91%	89%	30%	34%	33%	3%	98%	98%	86%
Base 2020	99%	99%	64%	95%	92%	33%	34%	33%	3%	98%	98%	86%
Woodland	98%	99%	58%	92%	92%	30%	33%	33%	3%	98%	98%	79%
LwEmSpr	97%	99%	55%	91%	89%	29%	33%	33%	3%	98%	98%	77%
Mitig1	97%	99%	54%	91%	89%	28%	33%	33%	3%	98%	98%	76%
Mitig2	97%	99%	52%	90%	89%	27%	32%	33%	3%	96%	97%	75%
Mitig3	97%	99%	51%	90%	89%	27%	31%	33%	3%	94%	92%	73%
Mitig4	97%	99%	45%	90%	89%	24%	29%	10%	2%	94%	92%	66%
Mitig2 NVZs	98%	99%	59%	94%	92%	32%	33%	33%	3%	96%	97%	75%
Mitig4 500 m	98%	99%	61%	92%	90%	31%	33%	33%	3%	98%	98%	84%
Mitig4 1 km	98%	99%	59%	92%	90%	30%	33%	33%	3%	96%	97%	83%
Mitig4 2 km	97%	99%	57%	91%	89%	28%	33%	33%	3%	96%	97%	81%
Mitig4 5 km	97%	99%	53%	90%	89%	26%	32%	33%	3%	94%	92%	77%
Mitig4 variable buffer	97%	99%	57%	94%	92%	30%	34%	33%	3%	98%	98%	81%
Mitig4 protectability	97%	99%	55%	94%	92%	28%	34%	33%	3%	98%	98%	80%

SSSIs 1 µg m^{-3}	England			Wales			Scotland			Northern Ireland		
	DWI	AWI	AWI-2	DWI	AWI	AWI-2	DWI	AWI	AWI-2	DWI	AWI	AWI-2
Base 2008	97%	97%	71%	90%	94%	32%	46%	17%	6%	95%	98%	91%
Base 2020	97%	97%	74%	92%	96%	35%	46%	17%	6%	95%	98%	91%
Woodland	97%	97%	69%	91%	94%	32%	45%	16%	6%	93%	97%	86%
LwEmSpr	96%	97%	65%	90%	94%	30%	43%	15%	5%	93%	97%	86%
Mitig1	96%	97%	65%	90%	94%	30%	43%	15%	5%	93%	97%	85%
Mitig2	96%	97%	63%	89%	94%	29%	42%	14%	5%	93%	97%	84%
Mitig3	96%	97%	62%	88%	94%	28%	42%	14%	5%	92%	94%	83%
Mitig4	95%	95%	57%	87%	94%	25%	40%	14%	4%	91%	94%	79%
Mitig2 NVZs	97%	97%	69%	91%	94%	33%	45%	16%	6%	93%	97%	84%
Mitig4 500 m	97%	97%	70%	91%	94%	32%	45%	16%	6%	94%	97%	90%
Mitig4 1 km	97%	97%	68%	90%	94%	31%	44%	16%	6%	93%	97%	89%
Mitig4 2 km	96%	97%	65%	89%	94%	29%	42%	14%	5%	93%	97%	87%
Mitig4 5 km	96%	97%	60%	87%	94%	26%	40%	14%	5%	92%	94%	83%
Mitig4 variable buffer	97%	97%	67%	91%	94%	32%	46%	17%	6%	95%	98%	87%
Mitig4 protectability	96%	96%	63%	90%	94%	30%	46%	16%	6%	94%	98%	84%

3.6. Cost-effectiveness of UK-scale scenarios

Cost estimates for UK NH_3 mitigation, for use in the modelling, were considerably out of date until June 2012, when a Defra sponsored workshop (led by Helen ApSimon) revised cost estimates (ApSimon *et al.* 2012). The workshop report allowed costs estimates to be built into the NARSES emission inventory calculations and mapping, and enabled the derivation of cost estimates for all mitigation scenarios. Table 8 shows estimated total costs for UK-wide mitigation scenarios and costs per kg NH_3 abated. It should be noted that costs of £19.8M associated with the projected implementation of BAT for pig and poultry farms by 2020 have been written off and are therefore not included in the comparison of the scenarios with the 2020 baseline here.

On average, all mitigation scenarios are substantially cheaper per kg NH_3 abated than older UK estimates (Webb *et al.* 2006), which had been considered as unrealistically high (UNECE, 2011). The new UK average abatement costs of £1-2 kg^{-1} NH_3 (Table 10) are similar to recent revised costs from across Europe (UNECE, 2011).

For the spatially targeted scenarios, the new cost estimates were applied proportionally to the emission reductions inside the buffer zones, thus arriving at different emission reductions and costs for SACs and SSSIs, respectively, due to their different spatial locations and extent. Cost effectiveness was assessed for all scenarios, and compared with protection effectiveness in terms of numbers and areas of SACs/SSSIs protected (see columns on the right hand side in Table 6).

Table 10: Mitigation costs, calculated using new cost estimates for mitigation measures from ApSimon *et al.* (2012), showing total costs for each UK-wide mitigation scenario and costs in £ kg^{-1} NH_3 abated.

Scenario	Emission (kt NH_3)	kt NH_3 reduced c.f. 2020	Costs (£M) c.f. 2020	Abatement cost £/kg NH_3
2020	218.5	-	-	n/a
LowEmSpr	186.2	32.3	37.3	1.15
Mitig1	184.2	34.3	52.0	1.52
Mitig2	179.2	39.3	62.7	1.59
Mitig3	177.1	41.4	80.7	1.95
Mitig4	160.6	58.0	84.7	1.46

In terms of cost-effectiveness alone, the UK-wide scenarios operate on a law of diminishing returns in order of increasing ambition, with only the most ambitious scenario reversing the trend. However, it is clear from the numbers and proportion of additional sites protected (for both the DWI and AWI), that the implementation of additional mitigation measures brings substantial benefits for UK SACs/SSSIs. **If the aim is purely to maximise protection, the most stringent measures applied over the largest area possible will always provide the largest benefit. However, if funds are limited, spatial targeting of measures can help prioritise measures where they provide the maximum benefit at the least cost.**

A comparison of cost-effectiveness between the UK-wide and the buffer zone scenarios shows that spatially targeted scenarios out-perform the evenly distributed mitigation significantly, for both SACs and SSSIs. The best value for money is obtained by the smaller buffer zones (500 m – 2 km).

Depending on whether the goal is to optimise cost-effectiveness using a) the Designation weighted indicator, b) the Area weighted indicator or c) a combination of a) and b), different scenarios achieve the best performance. For example, for SACs, the 500m buffer zones appear most effective using the Area weighted indicator, whereas for SSSIs the 1 km buffer zones and 2 km buffer zones are more cost-effective on the basis of cost/area protected. **In general, cost-effectiveness is reduced with larger fixed widths of buffer zones around both SACs and SSSIs, i.e. there are diminishing returns per unit cost.** This is due to not all sites requiring larger buffer zones to achieve non-exceedance of the 3 µg m^{-3} Critical Level, however exposure to NH_3 concentrations would continue to decrease with larger buffer zones, with concentrations expected to decrease further. If the target is purely to achieve non-exceedance of the 3 µg m^{-3} Critical Level, the variable buffer zones have more favourable average costs per site protected or per % area protected than the 5 km buffer zones around all sites. For the variable buffer zones, the required effort in overall emission reduction is much more similar to the 2 km buffer than the 5 km buffer for SACs, and virtually the same for SSSIs. This applies across all indicators, DWI, AWI and AWI-2 (see Table 6 for DWI and AWI, data for AWI-2 are shown in the Table 2 of ***Appendix 3***.)

The "Maximum protectability" scenario shows that, in theory, local reduction in emissions by an extra 6 kt NH_3 overall, in addition to the variable buffer zone scenario, would result in >80% of SACs that currently exceed the 3 µg m^{-3} Critical Level in the 2020 baseline scenario being protected. No cost-estimate was possible for the "Maximum protectability" scenario, as this involved a simple reduction in agricultural emissions in the affected grid squares, regardless of the type of sources or activities present. For SSSIs, an even higher proportion of sites appear "protectable" with such measures, however, it is estimated that this would require a further 15.5 kt NH_3 emission reduction, compared with the variable buffer zone scenario.

Although costs would be associated with the "additional trees" scenario, no costs are given here, as this scenario would have to be further refined, using information gained from the AC0201 project (Bealey *et al*., 2013).

3.7. Landscape scale modelling and assessment

To gain an insight into the differences mitigation measures may make for the N status of SACs/SSSIs, it is useful to investigate a selection of the UK-scale scenarios at the landscape scale, i.e. the scale of fields, farms and patches semi-natural vegetation. While UK-scale modelling is useful for providing the bigger picture and national statistics, the large spatial variability of NH_3 concentrations and N deposition across landscapes over short distances requires sub-grid analysis to assess mitigation measures in detail.

In this section, three example study areas are used to illustrate the estimated effects of mitigation measures across a range of typical agricultural landscapes of the UK: dairy + arable, beef + sheep + poultry, poultry + pigs + arable. As for the UK-scale assessment, uniformly applied vs. targeted measures were tested, and buffer zones created around example SACs and SSSIs. In addition, stricter measures were applied near sites, e.g. no landspreading of manures next to SACs/SSSIs. The difference in NH_3 concentrations due to the presence/absence of livestock buildings near SACs/SSSIs was investigated, to simulate e.g. permitting of additional poultry or cattle sheds. Additional illustrative maps are shown in ***Appendix 5***.

Note that the agricultural management data were collected between 5-12 years ago, with different levels of detail provided for sample fields. The emissions and exceedances derived from these data should be read as example scenarios and should not be taken as true representations of current conditions.

EXAMPLE 1 – Poultry + Pigs + Arable

In this landscape, NH_3 emissions and concentrations are dominated by a cluster of poultry and pig farms, interspersed with arable production and extensive grazing. UK-wide application of the most ambitious scenario (Mitig4) is anticipated to result in the local SACs' NH_3 status improving substantially, with NH_3 concentrations estimated to fall below the 3 µg m^{-3} Critical Level across all SAC areas in the landscape (Figure 9). Concentrations of NH_3 are also estimated to fall below 1 µg m^{-3} in large parts of the SACs, thus protecting not just higher plants, but also the most sensitive species, such as lichens and mosses.

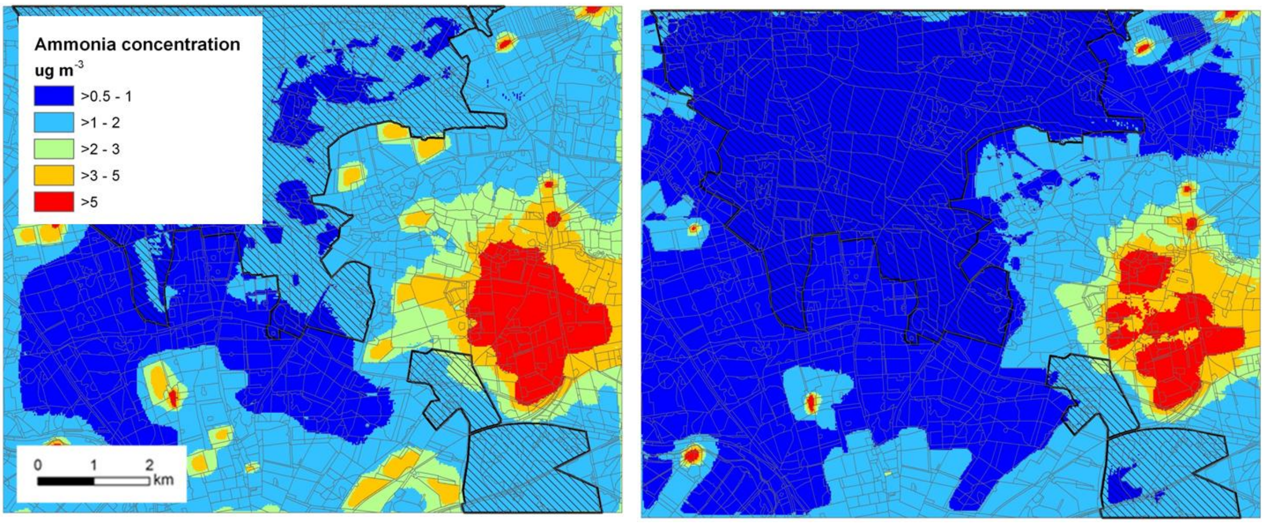
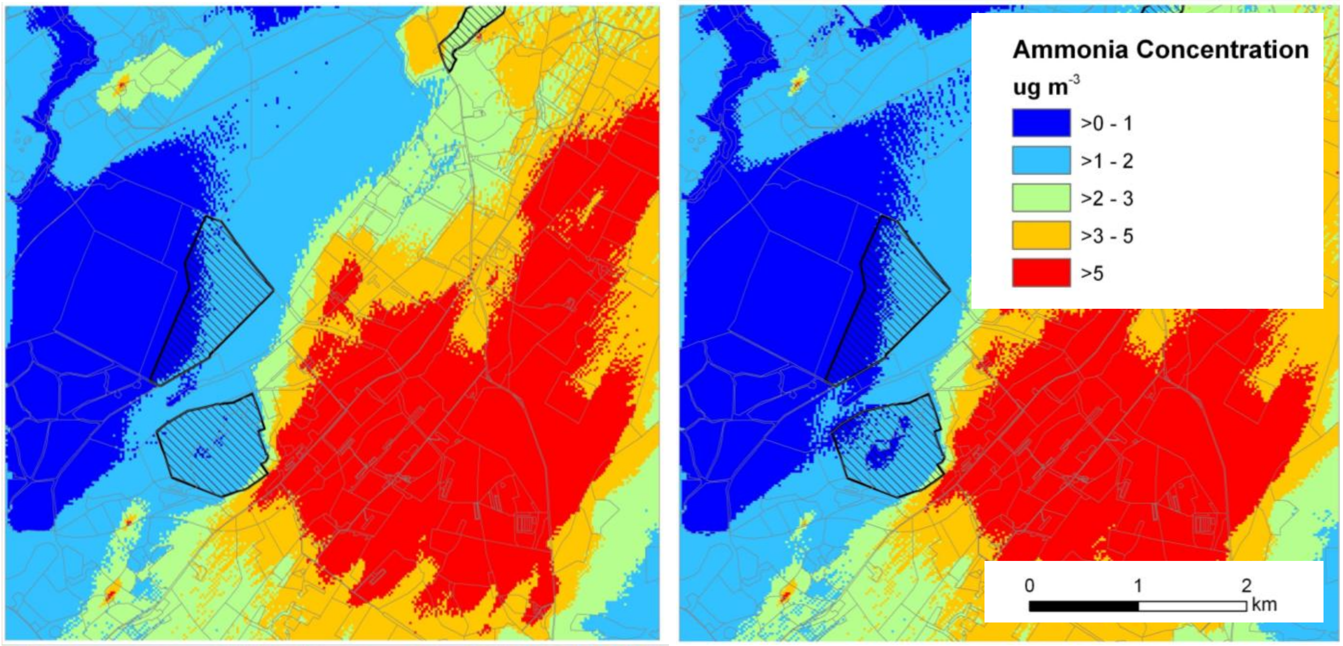


Figure 9:Concentrations of atmospheric NH_3 in a landscape with poultry, pig and arable farming in the vicinity of SACs, showing baseline concentrations (left) and landscape-wide application of the most ambitious mitigation scenario (Mitig4). SAC areas are delineated with cross-hatching. Landscape data source: NERC GANE/LANAS project (e.g., Dragosits *et al.* 2005).

EXAMPLE 2 – Poultry + Beef cattle & Sheep

Emissions in this landscape are also dominated by a cluster of poultry farms, with lower concentrations in the surrounding areas mostly extensively grazed by beef cattle and sheep. The two SSSI located in close proximity to the poultry cluster (several 100,000 birds), are, however, showing relatively low concentrations, due to their location away from the prevailing southwesterly wind direction (Figure 10, top left). If these sites were located at a similar distance to the northeast of the main emission sources, the 3 µg m^{-3} Critical Level would be substantially exceeded across their entirety. Adding two relatively small poultry sheds (55,000 birds in total) 1 km upwind of the southernmost SSSI would impact the site more than the estimated large agglomeration of birds elsewhere in the study landscape (Figure 10, bottom). This example shows how important it is to take account of local conditions when assessing where new installations could be placed without posing a risk to nearby designated sites.

It should be noted that the UK-wide and landscape-level Mitig4 measures considered in this study had little effect on NH_3 concentrations at the designated sites considered here, since the manure from the main poultry farms is not applied to fields in this landscape, but is transported further away (Figure 10, top right).



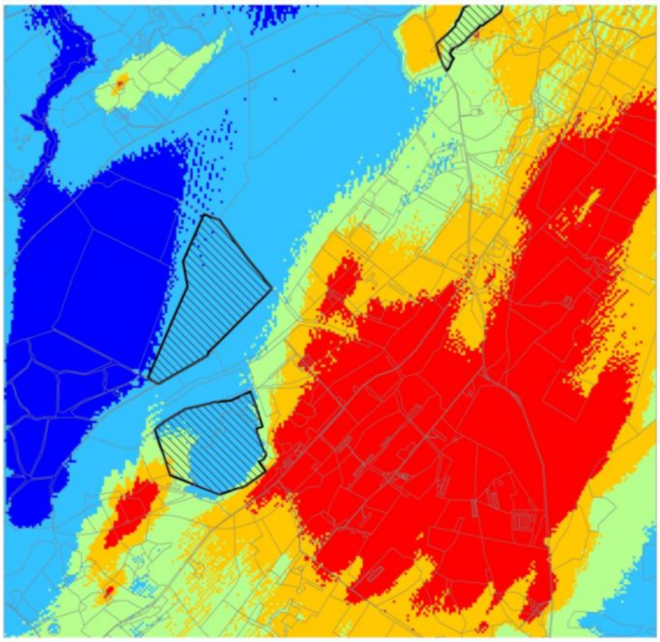


Figure 10: Concentrations of atmospheric NH_3 in a landscape with poultry, beef and sheep farming in the vicinity of SSSIs.
Top left: baseline concentrations and
Top right: UK- and landscape-wide application of the most ambitious mitigation scenario (Mitig4)
Bottom: baseline concentrations plus an additional poultry shed added in the SW corner, 1km from the nearest SSSI. SSSI areas are delineated with diagonal hatching.

Landscape data source: NitroEurope project (e.g. Vogt *et al.* 2013).

EXAMPLE 3 – Dairy cattle + Arable farming

This example illustrates a 2.5 km by 3 km landscape in the centre of a larger area with very high densities of dairy and arable farming. The small reserve near the top of the map exceeds the 3 µg m^{-3} Critical Level across its entirety, with concentrations in large parts exceeding 4 µg m^{-3}, both in the baseline scenario (Figure 11, top left) and under UK-wide implementation of the most ambitious mitigation scenario (Mitig4, Figure 11, top right). This site is one of the few SACs considered “not protectable” in the UK-scale assessment, i.e. even substantial additional reductions in agricultural emissions across a wider area (5 km radius of site) are not sufficient to bring the whole site below the 3 µg m^{-3} Critical Level.

To illustrate the level of measures required to benefit sensitive features at the site, all livestock housing and manure storage facilities were removed from a 1 km buffer around the SAC/SSSIs, in addition to full UK-wide implementation of Scenario Mitig4 (Figure 11, bottom). This resulted in estimated NH_3 concentrations decreasing to below the 3 µg m^{-3} Critical Level for at least parts of the SAC/SSSI near the top of the landscape. While such measures would not bring the entire site below the Critical Level, a decrease in average and peak concentrations or reduction in the periods of exposure would still provide benefits to the designated features.

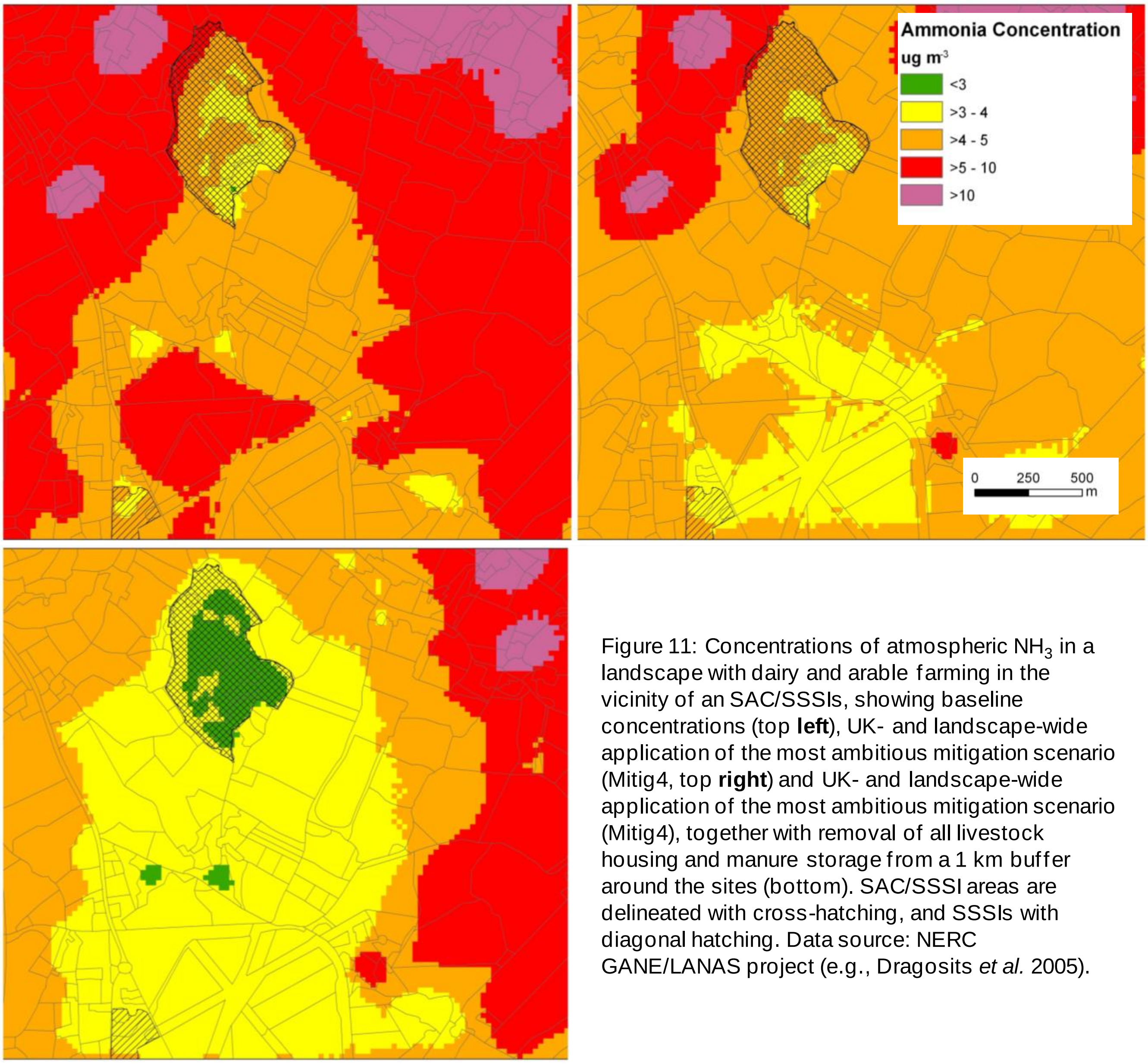


Figure 11: Concentrations of atmospheric NH_3 in a landscape with dairy and arable farming in the vicinity of an SAC/SSSIs, showing baseline concentrations (top **left**), UK- and landscape-wide application of the most ambitious mitigation scenario (Mitig4, top **right**) and UK- and landscape-wide application of the most ambitious mitigation scenario (Mitig4), together with removal of all livestock housing and manure storage from a 1 km buffer around the sites (bottom). SAC/SSSI areas are delineated with cross-hatching, and SSSIs with diagonal hatching. Data source: NERC GANE/LANAS project (e.g., Dragosits *et al.* 2005).

4. Implications of findings and policy recommendations

The UK- and landscape-scale scenario modelling discussed above has illustrated how **spatially targeted mitigation measures** can provide **cost- effective solutions for reducing excessive atmospheric NH_3 concentrations as well as dry deposition of reduced N originating from agricultural sources near SACs/SSSIs**. However, wet and occult (i.e. cloud) deposition of N over remote upland areas cannot be targeted as effectively in the same way, and larger overall reductions in emissions over wider areas are required to benefit sites mostly receiving excess N deposition through this pathway.

Depending on priorities, policy options could be optimised for combinations of given costs or protection targets, as shown by a range of example scenarios of different ambition levels. It is therefore possible that measures implemented specifically to reduce NH_3 concentrations below a targeted Critical Level (e.g., 3 µg m^{-3}), could still result in N Critical Loads remaining exceeded, especially where N deposition is above 10-15 kg N ha^{-1} yr^{-1}. In other words, while reducing concentrations will help towards addressing excess N deposition (i.e. by reducing AAE), total N deposition in parts of the UK would need to be addressed with more widely applied measures to decrease N emissions.

While it has been shown that protection for many SACs/SSSIs from NH_3/N deposition can be achieved with local measures, the statistical modelling of emissions, concentrations and deposition at the UK scale cannot take account of detailed local conditions, such as local wind directions, and individual farm management. Given these uncertainties, national-level recommendations/policies for **spatially targeted measures should be individually tailored on the ground with local expertise, to maximise effectiveness and minimise costs**. For example, low-emission buffer zones around an SAC/SSSI in an area with a strong prevailing wind direction would benefit from measures applied in larger areas upwind, whereas downwind much narrower buffer widths may be sufficient (as shown in the landscape scale examples, Section 3.7 above). Strategically placed tree belts around sources or upwind of an SAC/SSSI may be appropriate for some locations, but would not be work-able under all circumstances. Also, for very large sites with exceedance in only a small area, concentric buffer zones will not be the most effective measures, and measures should be tailored to target specific sources or source areas in such cases, to achieve cost-effective solutions. The **national scale assessment** can provide **indicators** that will help identify such sites, by combining site statistics on where exceedance occurs (DWI or AWI) with the % area exceeding (AWI-2). In these cases, it is essential that specific **local measures** are explored **on a case-by-case basis**, whereas small sites located in high concentration areas will benefit more from site-wide buffer zones with mitigation measures.

With regard to exposure to high levels of atmospheric NH_3 concentrations and N deposition, there are **large differences between the different regions of the UK**. Overall, SACs/SSSIs in Scotland are least exposed, whereas exceedance of both Critical Levels and Loads are largest across England and Northern Ireland, with intermediate levels of exceedance in Wales.

A simple assessment of **probability of exceedance** was carried out to explore predictability of exceedance at a sub-5 km grid resolution. Due to disclosivity agreements for agricultural census/survey statistics, this is the spatial resolution normally available for mapped emission data from agricultural sources being published. Figure 12 clearly shows areas with the highest probability of exceedance over wider areas of countryside (in red) to be co-located with the most intensive livestock farming areas. For example, the dairy areas of southwest England, Shropshire/Chesire, the Eden Valley, Ayrshire, SW Wales and Northern Ireland, as well as the areas with large-scale pig and poultry farming in East Anglia and Northeast England are well defined in this map. Designated sites in such areas with high likelihood of exceedance are more likely to be located close to substantial NH_3 emission sources and the associated higher NH_3 concentrations. Designated sites located in areas with low probability of CLE exceedance (in green) are associated with lower density emission sources, such as beef, sheep and arable farming, and upland areas in general. However, sites in these areas may still be at risk from local emission hotspots located in areas of generally less intensive agriculture with associated lower atmospheric NH_3 concentrations.

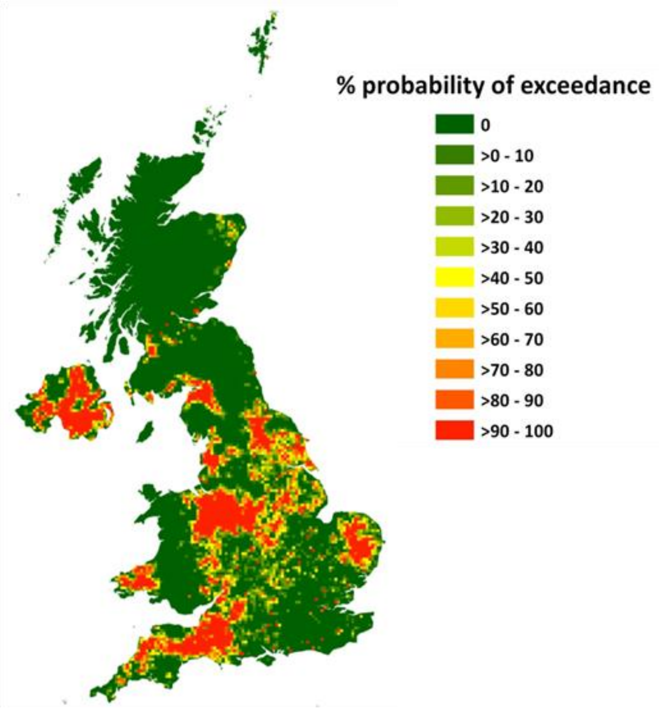


Figure 12: Probability of exceedance of the 3 µg m^{-3} Critical Level, derived from 1 km grid concentrations for the 2020 baseline scenario. If all 1 km grid cells constituting a 5 km grid cell exceed 3 µg m^{-3}, the probability of exceedance is 100%, if only 1 1 km grid cell exceeds, the probability of exceedance is 4%.

Given that development of new spatially targeted policies to protect SACs/SSSIs from NH_3 and N deposition effects would be a substantial effort, **existing spatial zonations** were **investigated** for their suitability. While **Nitrate Vulnerable Zones**, implemented spefically to reduce nitrate leaching, could be considered closely related in many ways, they have been shown to be **less suitable for the purpose of spatially targeting NH_3/N deposition effects on SACs/SSSIs**, due to their relative spatial locations, which do not overlap substantially over most of the UK. The exception to this is Northern Ireland, which has been designated an NVZ in its entirety.

For England, there is a close spatial relationship with existing targeted policies is the **Higher Level Stewardship Scheme**. Possible applications of NH_3 measures within this framework for the benefit of SACs/SSSIs are investigated in the following paragraphs.

Environmental Stewardship Scheme options for NH_3/N deposition

The following discussion refers to the **Environmental Stewardship Scheme** implemented in **England** only for the period 2007-14. [N.B. Different schemes are in place elsewhere in the UK. In Wales, the Glastir advanced agri-environment schemes use different target elements, such as carbon, water quality, biodiversity habitats and species, etc., with most areas of Wales being relevant for at least one of the target elements, and each farm being eligible for selecting measures targeting the element(s) prioritised locally. This is quite different from the HLS Scheme target areas in England, where the target areas cover ~1/3 of the country, with a wide range of options to select from, but not really targeting any particular "elements" (to use the Glastir terminology). The actual measures, on the other hand, are very similar to those available under ELS/HLS (see http://wales.gov.uk/docs/drah/publications/120803glastirte-paymentrates-managementopsen.pdf). The equivalent schemes in Scotland and Northern Ireland are the Rural Development Contracts, and the Countryside Management Scheme, both with entry level and higher level options.]

Current **land management options** under the Entry Level Stewardship Scheme (ELS) and its upland and organic strands, or Higher Level Stewardship Scheme (HLS) for protection of the natural environment are mostly targeted at protecting biodiversity (e.g., field margins, hedge rows), protecting water courses, and reducing greenhouse gas (GHG) emissions (Natural England 2010a, 2010b). [NB: ELS/HLS options designed to protect archaeological/ historic/ cultural features are not discussed here, except where co-benefits for environmental protections are noteworthy.] It is important to note that Environmental Stewardship is funded through the Common Agriculture Policy and this is undergoing a reform to fit with European priorities and budgets for the next financial perspective 2014-20, with the Environmental Stewardship Scheme likely to be revised.

There are currently **no ELS/HLS options directly targeted at reducing impacts of atmospheric NH_3 or N deposition to semi-natural ecosystems**. However, many ELS/HLS measures are relevant for NH_3 and N, and could be adapted to enhance protection of designated sites (SACs, SSSIs) from N related damage.

From the perspective of N deposition/NH_3, the existing measures can be grouped as follows:

- Reduced or no fertiliser and/or manure application in buffer zones, to improve biodiversity and/or prevent run-off. There are two types of these measures:
    - Location of measures fixed for the duration of the agreement
    - Location of measures not fixed for the duration of the agreement, but dependent on crop rotation (but overall area constant)
- Conversion of intensive agricultural fields to low N management (e.g., conversion to permanent grassland)
- Conversion of agricultural fields to semi-natural vegetation (e.g., wetland, heathland, raised bog, fenland, lowland raised bog).

The concept of buffer zones is implemented in many measures in both schemes, with narrow zones of 2-24 m being delineated along field boundaries (or mid-field for preventing run-off), or landscape features such as hedges, streams or ditches. From previous research (Dragosits *et al.*, 2006) on NH_3 concentrations or N deposition, such narrow buffer zones are expected to be of only minor benefit. Low-emission buffer zones (restricted fertiliser application <100 kg N ha^{-1} yr^{-1}, no urea, no slurry or manure applied) of 100, 300 and 500 m width around nature reserves were tested in that study. In the 500m buffer scenario of that study, both average and maximum dry deposition to the reserves was estimated to be reduced by ~5-25%, with the highest % values achieved with the 500 m scenario for small reserves surrounded by intensive agricultural activities. In addition to buffer zones, conversion of agricultural fields to semi-natural habitats could contribute to removing local N emission sources from the immediate vicinity of protected N sensitive sites.

Prioritising NH_3 measures under ELS/HLS (or its replacement scheme) near sensitive sites such as SACs/SSSIs could be a way to protect them from NH_3 pollution, with scheme advocacy and advice steering them to the best land management change, which would also include benefits to the farmers such as improving N use efficiency, and scheme payments providing an option for compensating farmers for loss of productive potential. The most environmentally effective land management options to use will be those able to deliver multiple benefits e.g. buffering against pesticide spray, creation or maintenance of semi-natural habitat that also provides a solution to NH_3 pollution. Since HLS (or its successor scheme scheme) agreements are likely to be targeted towards high value protected areas such as SSSIs/SACs, such an approach would support the achievement of NH_3 solutions either through bespoke management options or (more likely) adapting and seeking synergy with existing ones for habitat, soil and water management.

The current HLS target areas in England contain 88% of the terrestrial area of SACs in England, and 82% of the terrestrial area of SSSIs in England, with the current spatial extent of HLS target areas also providing the opportunity to implement buffer zones for mitigation measures (whether emission reduction measures or de-intensification) in the immediate vicinity of many SACs/SSSIs (Figure 13).

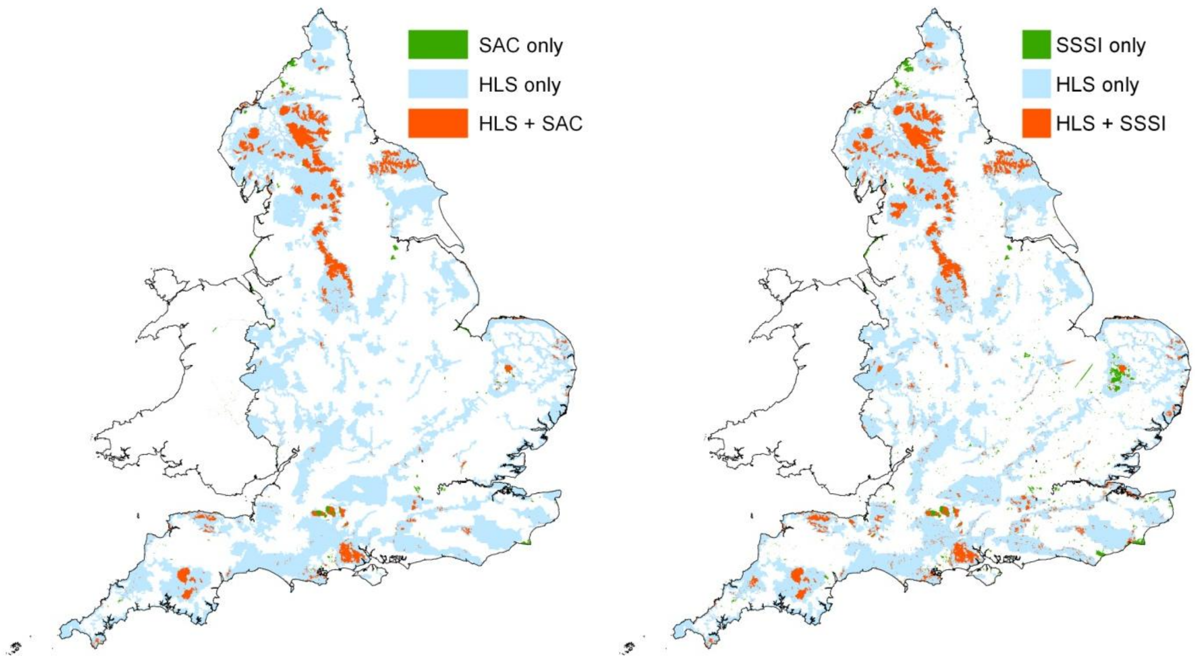


Figure 13: Overlap between current (2012) Higher Level Stewardship (HLS) target areas in England and SACs (left) and SSSIs (right), respectively. Areas in red show SACs/SSSIs that are already inside current HLS target areas, and areas in green show SACs/SSSIs not currently overlapping HLS target areas. Data provided by Natural England.

5. Summary/Conclusions:

- Ammonia emissions and concentrations are estimated to change very little towards 2020, given predictions of future livestock populations and fertiliser application rates under business-as-usual scenarios and the current limited ambitions for mitigation. This is expected to result in little change on effects of atmospheric NH_3 for SACs/SSSIs. Further substantial planned reductions in NO_x deposition are estimated to decrease overall N deposition and Critical Loads exceedance towards 2020. However, deposition from agricultural NH_3 sources across the UK is predicted to decrease by only by small amounts, similar to NH_3 concentrations. [N.B. The forecast reductions in emissions of SO_2 and NO_x by 2020 will result in lower concentrations of acidic compounds in the atmosphere, which can be expected to slow down the rate of formation of ammonium aerosol and sustain higher NH_3 gas concentrations. This has been observed in Holland, and there is some evidence of this in the UK from FRAME modelling results, though further analysis of measurement data is needed (A.J. Dore, CEH, pers. comm.)]
- NH_3 mitigation measures need to be ambitious if Critical Level/Critical Loads exceedances are to be substantially reduced, both UK-wide and for SACs and SSSIs.
- Spatially targeted mitigation can be achieve reductions in NH_3 Critical Level exceedance at SACs/SSSIs that are nearly large as UK-wide mitigation scenarios, with the spatially targeted measures achieving a much higher cost effectiveness (by a factor of 3-7, depending on the scenario).
- The higher cost-effectivness of spatially targeted measures is due to the rapid decrease in NH_3 concentrations away from intensive sources and the close spatial interplay of sources and nature conservation areas in the UK. To a limited degree, spatially targeted mitigation can also help reduce NH_x dry deposition near sensitive sites close to sources.
- Due to the longer transport distances and correlation with high rainfall/upland areas, reducing wet deposition requires more substantial overall reductions in NH_3 emissions over wider areas, and spatial targeting is less effective here. To reduce deposition substantially in these areas, substantial national and international reductions in NH_3 emissions are required.

- In conclusion, it can be inferred from the scenario work that a mixed approach, combining UK-wide mitigation measures of modest ambition with locally targeted measures of higher ambition near sensitive conservation sites, would result in protecting the largest numbers and areas of SACs/SSSIs and UK semi-natural vegetation.
- It should be noted that there are significant differences between UK-wide results and the individual countries (compared with each other and with the UK-wide results) which could result in different conclusions in each case. The difference between the baseline scenarios and the measures is much greater for England, than UK-wide, for example, suggesting that it is not appropriate to consider the data at the UK level alone.
- The UK scale modelling is representative at the national scale, however local conditions need to be taken into account on the ground for maximising benefits of measures for individual sites.
- Spatially targeted measures could be implemented locally via incentive schemes for land management change, such as the successor to Environmental Stewardship for the period 2014-20, with existing options being adapted for atmospheric NH_3 and targeted appropriately. This could include buffer zones of low-emission agriculture or extensification, application of technical measures, as well as agro-forestry measures through strategic tree planting (see project AC0201 for details on tree belts). While there is substantial potential for establishing a generalised framework for such an approach, such a framework would benefit from implementation though locally tailored decisions. These could be developed in collaboration between farmers, farm advisors, local authorities and the conservation agencies.

6. Future research priorities

Future research could include:

- Further investigations into suitable measures that could be spatially targeted, including co-benefits and trade-offs, costs and effectiveness where these have not been fully established yet. This could include landscape scale concentration measurements and modelling for buffer zone approaches.
- While a large suite of measures for reducing NH_3 emissions exists and has been implemented elsewhere through regulatory approaches (e.g. Denmark, The Netherlands), very little in the way of appropriate delivery mechanisms for such measures is currently available in the UK, apart from the Industrial Emissions Directive (formerly IPPC), which requires the implementation of Best Available Technology for large pig and poultry farms. Suitable delivery mechanisms for delivering targeted approaches, e.g. via voluntary/incentive schemes (such as agri-environment schemes, woodland grant schemes), could be investigated.
- An approach for estimating Critical Level exceedance was developed under this project, using different metrics such as the Designation and Area Weighted Indicators (DWI, AWI, AWI-2), together with improved spatial resolution of the atmospheric transport modelling for NH_3 from a 5 km to a 1 km grid scale. Following thorough testing during the project, this approach could be implemented for regular calculations at several levels, UK-wide and specifically for designated sites, such as SACs and SSSIs. [N.B. Some of this has already been included in the current Defra Critical Loads contract.]

7. Further actions resulting from research (Knowledge exchange)

- Two ammonia seminar days were held, in London and Edinburgh, bringing together policy staff from government departments (Defra and devolved administrations) and the different agencies (e.g., JNCC, EA, SEPA, NIEA, NE, SNH), organised through this project. The events included presentations from this and two related projects (Agroforestry Systems for Ammonia Abatement (AC0201), Agricultural NH_3 emissions as a source of UK secondary aerosol and the effect of emission abatement measures (AC0103)), preceded by an introduction on the role of NH_3 in the UK pollution climate and spatial/temporal trends (RoTAP, 2012).
- A further knowledge exchange event held was held through Webinar format, requested by for Natural England. Feedback from these events has been used to improve this report.
- Scientific papers are being drafted from this work, for publication in the peer-reviewed literature (UK scenario modelling, landscape).

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9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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