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Nitrogen Futures

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Summary

Background, aims and objectives

Atmospheric nitrogen (N) pollution is a major threat to UK biodiversity, leading to impacts including loss of sensitive species of plants, lichens and animals. Atmospheric N pollution is also a large risk to public health. Effects on ecosystems occur through direct impacts from elevated concentrations in the air, and through deposition of N compounds onto vegetation and soils which can lead to acidification and over-enrichment (eutrophication). There is strong evidence that N pollution has driven local extinctions of plant and lichen species across the UK, and increasing evidence of impacts on fungi, insects, birds and other animals. All of these are important components of biodiversity and contribute to ecosystem functions such as soil formation and nutrient cycling.

The key atmospheric N pollutants are ammonia (NH_3) originating mainly from agricultural sources and oxides of nitrogen (NO_x) mainly from combustion sources. While UK NO_x emissions have decreased substantially over recent decades through mitigation efforts, ammonia emissions have only marginally decreased in recent years and in parts of the UK even increased. Further mitigation especially of NH_3 emissions is needed to meet policy objectives to improve air quality and lower the impact of atmospheric N pollution on the environment and public health. Key policy objectives are those set by the National Emissions Ceilings Regulations (NECR), the UK Government's Clean Air Strategy (CAS) and 25 Year Environment Plan, and equivalent strategies in the Devolved Administrations. Previous work (e.g. Defra project AC0109, Ammonia Future Patterns), showed that spatial targeting of mitigation near sensitive habitats and sites can be cost-effective and has led to approaches such as Shared Nitrogen Action Plans (SNAPs) for designated sites.

The main aims of the study were to update and further develop the UK evidence base on the effectiveness of spatial targeting of mitigation measures and to test a range of potential options for future UK policy development. Specifically, the study aimed to develop detailed scenarios for 2030 and beyond, at different levels of ambition and to evaluate them in terms of environmental benefits. Outputs were provided at country (England, Wales, Scotland and Northern Ireland) and UK level, also taking account of within-country spatial variability. Additionally, local case studies assessed whether outputs from UK-scale models can identify atmospheric N pressures at designated sites and whether spatial targeting of mitigation is a suitable strategy to decrease atmospheric N effects at these sites.

Methods

Scenarios were developed using the latest available projections and policy targets for 2030, by comparing two main approaches: uniform UK-wide application of mitigation measures, or spatially targeting the same measures near designated sites. The focus was on Sites of Special Scientific Interest (SSSI), with concentric buffer zones representing scenarios that can be summarised as a) Emission Reduction Zones (ERZ), b) Emission Displacement Zones (EDZ), and c) combined optimised scenarios.

For the UK-scale assessment, the tools, models and datasets used for annual UK government reporting were applied, at a 1 km grid resolution. This included:

- detailed emission modelling to determine the magnitude and spatial patterns of atmospheric N emissions for 15 scenarios;
- chemical transport modelling to estimate atmospheric concentrations and deposition;
- calculation of critical loads and critical levels exceedances for sites and sensitive priority habitats.

For the local case studies, 15 sites across the UK were selected covering a wide range of habitats, atmospheric N sources and inputs. The case studies used the national-scale data together with re-analysis of previous local studies and local knowledge.

Results

The scenario modelling predicts a substantial decrease in impacts on sensitive vegetation by 2030 under the most likely future baseline. This assumes that NECR targets will be met through implementation of the UK National Air Pollution Control Programme (NAPCP), with modifications to suit the Devolved Administrations. This is estimated to achieve the UK Government's CAS target for England, defined as a *17% decrease in total reactive N deposition onto protected priority sensitive habitats*, with a predicted 18.9% decrease from the 2016 base year. More ambitious scenarios exceeded the target by a wider margin, thereby enabling further progress towards the targets of the UK Government's 25 Year Environment Plan ("restoring 75% of terrestrial and freshwater protected sites to favourable condition, securing their wildlife value for the long term").

The spatially targeted scenarios were generally more cost effective than the UK-wide implementation of the same measures in terms of decreased exceedance of critical loads and levels per unit of emission reduction. When compared with 2017, the 2030 baseline scenario that meets NECR emission reduction targets is estimated to result in 106 additional SSSIs no longer exceeding the 1 μg m^{-3} ammonia critical level (CLe), out of 3,567 SSSIs in exceedance under the 2017 Baseline scenario. For the 3 μg m^{-3} ammonia critical level (CLe), 361 UK SSSIs were in exceedance of the 3 μg m^{-3} ammonia Cle, an additional 135 SSSIs are estimated to no longer exceed their critical level. In terms of Critical Loads (CLs) 4,202 SSSIs are estimated to be in exceedance of CLs under the 2017 Baseline (of 4,793 SSSIs with CL information) with an additional 279 sites coming out of exceedance under NAPCP+DA (NECR NOx).

The most effective optimised scenarios are estimated to bring an additional 280 and 123 out of critical level exceedance, for the 1 and 3 μg m^{-3} ammonia thresholds, respectively. For N deposition, up to 203 additional sites were brought below critical loads, with substantial decreases in the amount of excess nitrogen input for many sites that could not be brought out of exceedance.

In areas with high N emissions and concentrations local emission reductions were reflected in substantial decreases in local concentrations and dry deposition illustrating the benefits of spatial targeting for sensitive habitats and designated sites. By contrast, sites and habitats with few local sources and large proportions of atmospheric N input from regional/longer-range atmospheric transport, respond less well to local measures.

Emission Reduction Zones provide wider benefits than Emission Displacement Zones across the country. EDZs do not contribute to emission reductions overall but move high emission activities to a greater distance from designated sites. ERZ benefit both the sites they are designed for and other habitats and sites further away due to the decrease in N deposition associated with the emission reductions. EDZ are, however, expected to provide a useful local tool for de-intensification of areas immediately surrounding designated sites. Because they do not require further technical measures the implementation of EDZs is, on average, relatively low-cost when compared with the implementation of ERZs.

Within the UK, there are clear geographical differences. In Northern Ireland and the more intensive agricultural landscapes in England (e.g. Cheshire, Shropshire), there are generally higher levels of excess atmospheric N input to sensitive habitats and designated sites. As a result, larger efforts are required to bring these out of exceedance, compared to elsewhere.

The local assessment showed that the UK-scale data are useful to identify atmospheric N pressures at site level and to evaluate whether spatial targeting of measures would be effective. While the overall level of threat can be identified together with likely nearby sources, the 1 km grid resolution may mask acute local gradients in atmospheric N concentrations and deposition, potentially underestimating local enhancement and the importance of “hotspots” such as large livestock houses or busy roads next to sites.

Conclusions and recommendations

The project provided a major update to the evidence base for informing policy development on the environmental outcomes of meeting 2030 NECR targets and impact of tested mitigation scenarios on the CAS “17% target”. It assists the development of future agri-environment schemes, in particular goals regarding “spatial targeting” and “landscape scale land use change” outlined in a current consultation for England, and tests outcomes of potential regulatory action for large cattle farms, as stated in the CAS. This was achieved through high resolution modelling with substantially updated modelling tools at a 1 km grid resolution with a new base year (2017, previously 2008), for the new NECR target year (2030, previously 2020), the latest UK and DA government thinking on ammonia and NO_x mitigation, and included recently developed metrics.

Results clearly illustrate that targeting zones surrounding sites is the most efficient and cost-effective solution for implementing mitigation measures, per unit of emission reduction. At a site level, targeting measures within buffer zones can be almost as effective as applying measures UK/country-wide, in terms of reducing atmospheric N input. It is important to note though that wider measures will benefit sensitive habitats beyond protected sites. The characteristics of the site and the principal emission sources contributing to atmospheric N input are key for predicting whether spatial targeting is effective.

Overall, the scenario analysis showed that there is no single “one size fits all” solution that will be the most effective approach across all parts of the UK. Instead, the concepts of Emission Reduction and Displacement Zones could be implemented as part of a framework with suitable measures and zones tailored for ambition levels and local sources. This “smart targeting” of measures, nested within and combined with UK or country-wide efforts, such as those planned under the NAPCP, could provide environmental benefits across large numbers of designated sites. Wide efforts, such as those planned under the NAPCP, could provide environmental benefits across large numbers of designated sites.

The effectiveness of the modelled spatial targeting measures varies across the UK, the four countries and between sites. This is due to the make-up and density of the emission source sectors near each site and the ability to influence concentrations or deposition through the measures tested. For example, most sites in the Scottish Highlands and Islands are exposed to little atmospheric N input from local sources. This means that decreasing deposition to these sites depends on ambitious mitigation elsewhere in the UK. In Northern Ireland, high emission densities from agriculture mean that much of the atmospheric N input originates within the country. Therefore, both ambitious country-/UK-wide measures and local targeting are required to decrease the current very high ammonia levels. Wales is characterised by a mix of relatively clean and remote upland areas that mostly receive their atmospheric N input from a wider region, including England, and high emission densities in other parts, e.g. near the English border and in dairying areas such as Carmarthenshire. Sensitive habitats in England’s lowlands are often embedded in intensive agricultural landscapes and many upland areas are close to urban and/or rural sources of atmospheric N. Therefore, measures that decrease emissions both locally and regionally will provide benefits across the country.

Designated sites that are subject to high levels of local atmospheric N input, from either farming activities or road transport, could be effectively targeted with local measures. By contrast, for sites remote from local emission sources, the main drivers for improvement are wide-ranging national and international mitigation efforts, such as the current NECR targets.

In summary, it is recommended that consideration should be given to an optimised two-pronged approach, combining UK-wide and locally targeted measures:

- Ambitious UK-wide measures to decrease emissions with appropriate adaptation by the DAs, or similarly ambitious country-led measures to decrease emissions and their resulting impact across the UK, within and between the countries. This provides benefits in both source areas and remote areas with high proportions of long-range atmospheric N input working towards decreasing effects across both sensitive priority habitats and designated sites.
- Spatial targeting where appropriate, e.g. by selecting locally relevant, appropriate and sufficiently ambitious measures from a “tool kit” and implementing these in Emission Reduction Zones. Local emission reductions can achieve substantial local benefits. For targeting to be successful, both in terms of environmental benefits and local engagement, a clear framework for identifying priority actions needs to be in place, with a menu of options that can be selected for optimal local outcomes.

Contents

1 Introduction

1.1 Project aims and overview

The project aims to update and further develop the UK evidence base on the effectiveness of spatial targeting of emission mitigation for atmospheric nitrogen emissions of NH_3 and NO_x and quantify their impact on a range of potential options for future policy development. This is to inform policy development at UK, country and local scale to optimally locate mitigation measures for maximising benefits to ecosystems, priority habitats and designated sites while achieving overarching national targets.

The following objectives were set out to achieve these aims:

- to develop quantitative spatial datasets for 2030 emissions of NH_3 and NO_x, building on future projections of source activities (for Business as Usual (BAU) and National Air Pollution Control Programme (NAPCP) scenarios, based on the most recent available data);
- to develop spatial targeting scenarios for 2030 (and beyond), based on bundles of appropriate measures, taking account of their effectiveness and cost as well as considerations of feasibility and barriers to implementation (including data on regional variability of these, where available). A focus was on measures that could be implemented under future agri-environment schemes for NH_3, across the UK and Devolved Administrations (DAs);
- to develop a set of metrics for assessing ecosystem benefits of scenarios and evaluating against policy objectives;
- to model the implication of the scenarios developed on emissions, concentrations, deposition and vegetation effect metrics of atmospheric N (NH_3, NO_x), for ecosystems, priority habitats and designated sites, at the UK and country level (England, Wales, Scotland, Northern Ireland);
- to evaluate the scenarios against policy targets and in particular, the difference between UK-wide scenarios and spatially targeted scenarios, in terms of emission reduction, costs, and benefits to the environment;
- to analyse the scenarios for the relative importance of NO_x and NH_3 contributions to reductions in emissions and N deposition across the UK and DAs, taking account of the spatial variability, including of oxidised vs reduced and wet vs dry N deposition;
- to test whether the local implementation of the optimised scenarios is effective, through a number of local case studies for designated sites across the UK and the DAs; and
- to qualitatively analyse and assess co-benefits/trade-offs with other issues such as GHG emissions, water quality and human health, across UK, DAs and local scales.

1.2 Atmospheric N emissions, concentrations, deposition and effects on ecosystems - current status and outlook

Atmospheric nitrogen inputs to sensitive ecosystems are a major threat to UK biodiversity (RoTAP 2012; Emmett *et al.* 2012; Natural England 2015; JNCC 2019a, 2019b; Dragosits *et al.* 2015; Bealey & Dore 2017), both through:

- atmospheric deposition of N compounds (including wet and dry deposition of oxidised and reduced N); and
- direct impacts from elevated concentrations of ammonia (NH_3, mainly from agricultural sources) and oxides of nitrogen (NO_x, mainly from combustion sources).

NO_x (and SO_2) emissions in the UK and across the European continent have been substantially reduced over recent decades through international and national mitigation measures for combustion sources. This is due mainly to measures applied to industry, and to a lesser extent transport sectors, over the last decades, with mitigation efforts continuing. Although significant human health issues related to NO_x remain, especially in urban areas, the degree of progress has been much faster than for NH_3 emission mitigation.

The latest published UK report on trends in critical load (CL) and critical level (CLe) exceedances (Rowe *et al.* 2020)[1] provides detailed tracking of ecosystem effects over time, using rolling 3-year mean datasets (Table 1-1). The report series provides evidence of the declining risk to UK habitats and species from acidification, mainly due to decreases in sulphur deposition. Seventy seven percent (77%) of habitats (by area) are estimated to have exceeded their acidity critical loads in 1996, decreasing to 39 % in 2017. For habitats at risk from excess nitrogen, i.e. eutrophication, the area with exceedance fell from 75% in 1996 to 58% in 2017, mainly due to decreases in NO_x deposition. Excess nitrogen, i.e. average accumulated exceedance of the critical load, decreased from 9.5 kg N ha^{-1} yr^{-1} in 1996 to 5.2 kg N ha^{-1} yr^{-1} in 2017. This reduction in exceeded area was largely driven by N deposition onto habitats in Scotland falling below critical loads. Decreases in the proportion of designated sites exceeding their nutrient-N critical load, for one or more designated features, from 1996-2017 are small, at 7.1% for SAC and 10.1% for SSSIs, reflecting the smaller decrease in N deposition compared with acid deposition. The largest decreases occurred in Scotland, at 13% for SACs and 19% for SSSIs. In regions with higher deposition such as England, the national decreases in deposition were less effective in bringing large areas of deposition below critical load thresholds.

In terms of exceedance of the NH_3 critical levels, 5% of the UK land area in 2016 (Rowe *et al.* 2020) exceeded the 3 μg m^{-3} threshold set for higher plants and 63% exceeded the 1 μg m^{-3} threshold set for lichens and mosses. There have only been minor changes in these metrics since 2010 with small increases for the 3 μg m^{-3} critical level and small decreases for 1 μg m^{-3}. Sixty percent (60%) of UK SACs and 70% of SSSIs are currently estimated to receive NH_3 concentrations above 1 μg m^{-3} (based on the maximum concentration estimated at each site), and 8% of SACs and 5% of SSSIs currently receive NH_3 concentrations above 3 μg m^{-3}, with variations across the UK (Table 1-1).

Table 1-1. Current status of exceedance of nutrient N critical loads and NH_3 critical levels for N-sensitive habitats, SACs and SSSIs in the UK (Trends report 2020). Excess N (AAE) refers to the amount of N deposition above the critical load. SRCL refers to site-relevant critical loads. Not all sites have SRCLs assigned.

	England	Wales	Scotland	NI	UK
Critical Loads exceedance (units: as stated)					
N-sensitive habitat % area exceeded	95.1	87.6	34.0	81.2	57.6
Excess nitrogen for habitats (AAE) kg N ha^{-1} yr^{-1}	11.5	8.1	1.8	7.3	5.2
SAC % sites (with SRCL) exceeded	94.4	94.9	76.1	98.0	87.9
SSSI % sites (with SRCL) exceeded	85.9	97.1	71.5	88.3	84.8
Critical Level exceedance (units: %)					
Land area exceeding 1 μg m^{-3} critical level	87.9	56.3	17.9	90.8	62.9
Land area exceeding 3 μg m^{-3} critical level	6.3	1.0	0.1	27.3	5.1
N-sensitive habitat exceeding 1 μg m^{-3} critical level	64.6	28.4	3.2	75.2	25.4
N-sensitive habitat exceeding 3 μg m^{-3} critical level	1.9	0.1	0.0	9.2	1.0
SAC sites exceeding 1 μg m^{-3} critical level	91.3	72.9	17.1	90.7	60.6
SAC sites exceeding 3 μg m^{-3} critical level	11.3	4.7	0.0	18.5	7.7
SSSI sites exceeding 1 μg m^{-3} critical level	87.3	61.8	24.5	88.6	70.4
SSSI sites exceeding 3 μg m^{-3} critical level	5.8	2.7	0.4	16.3	4.7

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[1] Trends Report 2020: Trends in critical load and critical level exceedances in the UK http://www.cldm.ceh.ac.uk/sites/cldm.ceh.ac.uk/files/2019%20TRENDS%20report.pdf.

1.3 Current status of policies and developing policy landscape

The UK is a signatory of the UNECE Convention on Long Range Transboundary Air Pollution (CLRTAP) and was signatory to the EU Directive on the Reduction of National Emissions (2016/2284)[2], known as the "new" NECD in 2016. The requirements of the new NECD were enshrined in UK law as the National Emissions Ceilings Regulations (NECR)[3], and therefore continue to be in force since the UK has left the EU. Under these obligations, the UK is required to achieve national emissions reductions for several air pollutants – SO_2, NO_x, $PM_{2.5}$, NH_3, NMVOC and black carbon and to develop a National Air Pollution Control Programme (NAPCP) to attain these limits.

The UK Government's Clean Air Strategy (CAS) (Defra 2019a)[4] and 25 Year Plan (Defra 2018a)[5] outline ambitions for cleaner air and for potential regulatory approaches for NH_3, while wider agri-environment schemes are currently being reviewed and redesigned (Defra 2020)[6]. This recently published consultation document for England explicitly focuses on "locally targeted environmental outcomes" and the need to "use some form of spatial targeting and local planning" (Tier 2) and "landscape scale land-use change projects" (Tier 3). Depending on the detailed outcomes a substantial expansion of NH_3-relevant mitigation measures is anticipated. The publication of a new Code of Good Agricultural Practice (COGAP) (Defra 2018b)[7] for the prevention of NH_3 emissions in England is also a significant step forward, providing compliance with the requirements of Annex IX of the Gothenburg Protocol, while presenting an opportunity for much wider dissemination and mainstreaming of approaches to minimise NH_3 emissions.

For NH_3, only a small proportion of UK emissions are currently regulated, e.g. large pig and poultry farms under the Industrial Emissions Directive/Environmental Protection Regulations for England and DA equivalents. Regulation is effectively operated through the planning system for other sources, via planning permissions. This limitation provides a high dependence on the success of voluntary action, which is a major challenge for meeting the NECR targets for 2020 and 2030. The NECR targets require emission reductions of 8% and 16% respectively of ammonia, compared with the relevant 2005 baseline emission levels.

In this wider context, it is important that there is good quantitative understanding of the potential benefits of spatially targeted NH_3, NO_x and N deposition measures. The comprehensive assessment carried out under Defra project AC0109 (Ammonia Future Patterns (Dragosits *et al.* 2014) is now out of date and requires an update, for the following reasons:

- The future projected target year for the analyses was 2020, with a 2008 base year – the horizon now is towards 2030 and beyond;
- Policy drivers have changed, with the revised NECD/NECR targets for NH_3 much more ambitious, and further NO_x reductions planned and in progress to 2030, the NAPCP, CAS and various amended habitats regulations and biodiversity strategies;

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[2] NECD https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2016.344.01.0001.01.ENG.

[3] NECR https://www.legislation.gov.uk/uksi/2018/129/contents/made.

[4] Clean Air Strategy (2019) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770715/clean-air-strategy-2019.pdf.

[5] A Green Future: Our 25 Year Plan to Improve the Environment (2018) https://www.gov.uk/government/publications/25-year-environment-plan.

[6] Environmental Land management: policy discussion (opened Feb 2020, currently paused due to COVID-19, Apr 2020) https://consult.defra.gov.uk/elm/elmpolicyconsultation/; discussion document https://consult.defra.gov.uk/elm/elmpolicyconsultation/supporting_documents/ELM%20Policy%20Discussion%20Document%20230620.pdf.

[7] Code of Good Agricultural Practice for reducing ammonia emissions (2018) https://www.gov.uk/government/publications/code-of-good-agricultural-practice-for-reducing-ammonia-emissions.

  - Agri-environment schemes are currently being developed, with NH_3-relevant measures/options being considered for implementation (Defra/NE project AROMA LM047510, Carnell *et al.* 2019a);
  - UK government and Devolved Administrations are developing strategies for NH_3 emission mitigation and there has been a focus on human health impacts for both NO_x and NH_3 in the media;
  - The modelling tools used under project AC0109 have been updated substantially, with:
    - a new non-disclosive 1 km emission version of the AENEID model (Carnell *et al.* 2019b), providing annually updated maps for the UK National Atmospheric Emission Inventory[8], building on the revised UK Agricultural GHG and Ammonia Emission Inventory model;
    - a new calibrated 1 km concentration and deposition modelling capability for the established UK FRAME model (Fine Resolution Atmospheric Multi-pollutant Exchange), which is used under Defra's National Focal Centre project for input to critical loads and levels exceedance modelling. The 1 km critical loads and levels exceedance modelling capability are now adapted to work with new 1 km grid concentration and deposition data;

- A number of studies, which brought further insights into spatial targeting of mitigation measures, have been carried out since project AC0109 was completed. These include:
    - RAPIDS, Defra Contract AQ0834 (Dragosits *et al.* 2015), which investigated measures and delivery mechanisms to reduce atmospheric N input to designated sites;
    - Site categorisation and assessment for atmospheric N inputs and mitigation - Natural England IPENS-49 and IPENS-50 (Natural England 2015), NRW AAANIS project (Carnell & Dragosits 2015), NIEA EMIND project (Carnell & Dragosits 2017);
    - DAERA ammonia projects linked to Making Ammonia Visible report (Gilliland *et al.* 2017);
    - Defra Ammonia Futures – investigating feasibility of and barriers to NH_3 measures in England through regional workshops, trade-offs and costs (Wiltshire *et al.* 2019); and
    - Defra National Air Pollution Control Programme 2018-2020 – scenarios on cost-effective achievement of NECD targets while maximising human and ecosystem health and crop benefits (Defra 2019b).

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[8] See naei.beis.gov.uk.

2 Methods

2.1 Future projections to 2030 and beyond for NO_x and ammonia

The most recent available projections to 2030 were used for the assessment of mitigation scenarios for 2030 and beyond under this project, underpinned by a baseline year of 2017. Emission projections are made annually as part of the NAEI (currently to 2030) and the most recent inventory submission combined with the latest agricultural activity data projections provided by the Food and Agricultural Policy Research Institute (FAPRI-UK data, provided by Defra – pers. comm.) was used in this project. The FAPRI activity data forecasts were used as provided in April 2019 and are more recent than those underlying the official UK projections listed in appendix to **Annex 1** (FAPRI forecasts from 2017).

With regard to emissions of $NO_{x,}$ existing data from the UK NAEI were used for 2017 and detailed sector projections were used for the 2030 BAU baseline, with further reductions to bring NO_x emissions in line with NECR national targets (see **Annex 1** for details on the projections used for the baseline data). To illustrate potential additional mitigation ambitions and their effects on emissions, two further scenarios were modelled: an additional reduction of NO_x emissions in urban agglomerations by 10% (all sectors) and, for all 2040+ scenarios, a further reduction by 15% across the UK (i.e. on top of the 10% in agglomerations by 2030) – see **Annex 2** for details of the scenario description, and **Annex 4** for the detailed quantification by sector for the scenarios.

2.2 Ecosystem benefit metrics

Different ways of measuring the benefits of decreases in N pollution were reviewed in a consultation with pollution scientists and policy experts, as described in **Annex 3**. These can be grouped as metrics that reflect:

1. Pollutant emissions, i.e. overall indicators of pressure on ecosystems;
2. Exposure, i.e. site and habitat-specific indicators of pressure;
3. Risks to sites designated for their nature conservation interest;
4. Likely effects on habitats over the short or long term, such as exceedance of critical load or critical level; and
5. Direct effects on ecosystem condition, such as species richness.

In the consultation, sets of essential and desirable criteria were established for deciding what makes a metric useful for assessing and communicating the benefits to ecosystems of decreased N pollution. Metrics potentially useful to report were short-listed and those that fulfilled essential criteria (e.g. with an acceptable level of uncertainty and sufficiently sensitive to express meaningful change over the study period) were ranked according to the desirable criteria.

Desirable characteristics used in the selection of informative metrics are listed in **Annex 3**, along with the weights ascribed to each. In general, metrics were considered more desirable if they are readily understood, sensitive to change, and relevant to stakeholders at different scales such as site managers and policy makers at country or UK scale.

Predictions can be made for different scenarios of changes in ecosystem condition (group 5 above), such as changes in species richness or habitat suitability for positive indicator species. Such endpoint metrics are useful for communicating ecosystem impacts but involve extra uncertainties in terms of modelling changes in soil and vegetation biogeochemistry, and species responses. For this reason and because of time constraints, we report on scenario impacts only in terms of pressure metrics (groups 1 and 2) and indicators of risk to sites and habitats (groups 3 and 4). The metrics used to illustrate the scenarios in this report are summarised in Table 2-1.

Table 2-1. Metrics used in this report (units given in brackets for each metric).

Type	Metric
Emissions	Agricultural emission density around designated sites (concentric zones) – measure of local pressure [kg N ha^{-1} yr^{-1}]
	Local spatial emission reductions (e.g. within buffer zones surrounding designated sites) [kt N yr^{-1}]
	Sectoral emissions reductions (e.g. NH_3 by livestock category) [kt N yr^{-1}]
	National (UK) Emissions reductions (NH_3, NO_x) [kt N yr^{-1}]
	Regional emissions (NH_3, NO_x) – Devolved Administration level (E, W, Sc, NI) [kt N yr^{-1}]
Exposure	Annual deposition of total N (vegetation specific) [kt N yr^{-1}]
	Atmospheric concentration of NH_3 [µg NH_3 m^{-3}]
Habitat effects	Exceedance of critical level for ammonia: amount of exceedance [µg NH_3 m^{-3}]
	Excess Nitrogen [kg N ha^{-1} yr^{-1}]
	Exceedance of critical load for nutrient-N: amount of exceedance [kg N ha^{-1} yr^{-1}]
	Area of sensitive habitat where CL_{empN} is exceeded [% of total sensitive-habitat area]
	Area of protected sites (reported separately for SACs, SPAs and SSSIs/ASSIs) where CL_{empN} is exceeded for at least one sensitive feature ['000 ha]

Two main types of indicators were used to quantify the effectiveness of the modelled mitigation scenarios on designated sites. These refer to the proportions of designated sites exceeding critical levels and loads following the approach of Hallsworth *et al.* (2010) (Figure 2-1). This approach was applied in the preceding Defra AC0109 project, assessing both the number and area of designated sites as follows:

- **Designation weighted indicator (DWI)** - shows the proportion of sites with exceedance over at least part of the site, giving the same weight to each designated site, regardless of size. The rationale is that the designation of each site is 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 sites tend to be located in more remote and cleaner locations.
- **Area weighted indicator (AWI-1)** - 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. The AWI-2 needs to be considered in combination with the AWI, as the designated habitats and species in any protected site may or may not be located in the areas exceeded within sites. This indicator cannot quantify whether the designated features of a site would be protected or not, but shows of the percentage area of sites that are predicted to be below the CLe/CL. The DWI and the AWI, on the other hand, are more precautionary, in that they assume a site may be considered at risk when exceedance occurs in part of its area. This indicator should be used by comparing both AWI and AWI-2 between scenarios, rather than looking at them in isolation.

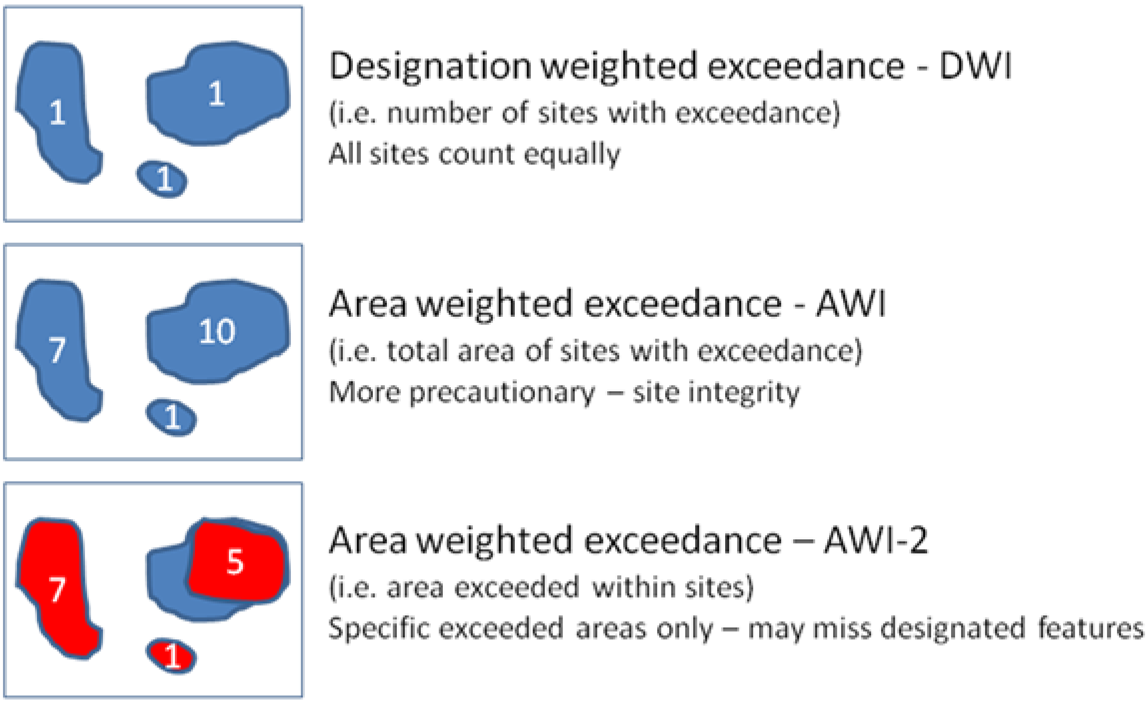

Figure 2-1. Graphical representation of indicators for quantifying the % of SACs/SSSIs exceeding a Critical Level (following the approach of Hallsworth *et al.* 2010, as applied in Defra AC0109).

2.3 Mitigation measures and scenario development

2.3.1 Approach to development of scenarios

The study required three different types of scenarios to be developed:

1. Baselines for 2030 (as realistic as possible, given current knowledge);
2. UK-wide and spatially targeted mitigation scenarios of different ambitions and with different types of measures for 2030 and 2040+; and
3. Optimised spatially targeted mitigation scenarios, requiring initial analysis of the scenarios under ‘2’ above before optimising in a second iteration.

All scenarios selected for modelling in this study are described briefly in Section 2.3.3 of this report. Further detail on methods are available from annexes to this report, as follows:

- **Annex 1** - development of the 2030 baseline scenarios, with underlying assumptions on how the UK will meet the NECR targets;
- **Annex 2** - development of the 2030 and 2040+ scenarios for testing spatial targeting vs UK-wide implementation of different ambitions and selection from a long list of potential options;
- **Annex 4** - implementation of the mitigation scenarios (including optimised scenarios) into high-resolution emission maps; and
- **Annex 6** - extended scenario description table - excel spreadsheet providing more details for the 15 scenarios modelled in a single larger summary table.

2.3.2 Available input data and information on measures

For the agricultural scenarios, the underlying data regarding livestock numbers, crop areas and fertiliser N use at country and UK level were kept the same as for the 2030 baseline, using FAPRI activity data forecasts as described in Section 2.1.

The same high-resolution annual agricultural statistics on livestock populations and areas of arable crops and grassland as for the 2017 UK agricultural emission inventory were used for the spatial modelling, under data agreements with the four countries' statistical departments. This makes the spatial distribution of emission sources carried out under the project directly compatible with the annual maps available for download from the NAEI (NAEI 2020[9]). Mitigation measures applied to the agricultural sector were each associated with an NH_3 emission reduction efficiency and an annualised cost. Reduction efficiency values are largely based on UK-based measurements (Misselbrook & Gilhespy 2019) or, where appropriate, using values from the UNECE TFRN Ammonia Abatement Guidance Document (Bittman *et al.* 2014). Implementation rates for the different measures at DA level for each scenario were agreed in consultation with the relevant policy groups in each DA (see Table 10 of **Annex 1** for implementation rates for the 2030 NAPCP+DA scenarios). A more detailed description of the methods is provided in Section 1 of **Annex 4**.

For the UK-scale implementation of spatially targeted measures around designated sites, a new boundary dataset of site boundaries updated to 2019 was prepared for this project. This is an update to the 2011 version that is operationally used in the NFC modelling. Before this can be updated in the NFC site database for official UK trends estimates, the designated features database needs to be revised with detailed information still needing to be collated and finalised with the relevant Country Nature Conservation Body (CNCB). For the purposes of this project, it was important to include newly designated or enlarged sites into the modelling, so that the emission, concentration and N deposition maps can later be re-analysed for new sites where critical loads are currently not in the database. Meanwhile, the concentration and N deposition outputs could already be analysed for the 2019 sites, and any concentration-based metrics quantified, as well as N deposition-based metrics for 127 SSSIs established since 2011. In other words, critical loads-based metrics for the newer sites could not be calculated for these 127 new sites, with calculations only possible for sites in the NFC database, i.e. those up to 2011.

2.3.3 Scenario options and selection of subset for implementation

To make the scenarios as relevant and useful as possible for input to future policy development, a wide-ranging consultation with the project Steering Group (member organisations listed in acknowledgements) was undertaken. The decision-making process started with a long list of possible scenarios that was assessed against key interests of the organisations involved with the aim to select 12 scenarios for detailed modelling and assessment.

Emissions of ammonia (NH_3) and oxides of nitrogen (NO_x) were estimated for all scenarios, building on the detailed analysis and assessment of the most recent available UK emission inventory datasets (2017), the 2030 baselines and mitigation scenarios established under this project. Because sulphur dioxide (SO_2) concentrations play a major part in atmospheric chemistry reacting with NH_3 and influencing its atmospheric lifetime and chemical transformation, emission baselines were also established. Tables 2-2 and 2-3 provide a summary description of all scenarios and the short scenario names used in this report. The derivation of all scenarios and underlying assumptions are described in detail in **Annexes 1** and **2** to this report. **Annex 6** provides a spreadsheet version of Table 2-3 with further details added.

For spatial targeting of NH_3 mitigation close to designated sites, Emission Reduction Zones (ERZ) and Emission Displacement Zones (EDZ) were modelled around the site boundaries, using 1 km, 2 km and 5 km distances in the study. In the EDZ scenario, emissions are not actually reduced overall across the country, but manure and slurry spreading is excluded

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[9] See naei.beis.gov.uk.

from 1 km zones around designated sites, with the related emissions “displaced” to beyond 2 km from the site boundaries, thereby resulting in increased emissions further away. The focus of these spatially targeted mitigation scenarios was on Sites of Special Scientific Interest (SSSIs) in Great Britain, and the equivalent Areas of Special Scientific Interest (ASSIs) in Northern Ireland. An additional scenario with ERZ (2 km zone) was carried out for Special Areas of Conservation (SACs), to determine any differences in effectiveness due to the geographical distribution of the two types of designated sites, differences in size, sensitivity of designated features, *etc*.

In terms of mitigation ambition, several levels were explored across the scenarios. For ammonia, the 2030 NAPCP+DA (NECR NO_x) baseline was determined by modelling the most likely “central estimate” of measures under the NAPCP, with additional input from the DAs to adjust the NAPCP assumptions that were mainly modelled for England in the NAPCP projections (data provided by Defra, for DA consultation). The next higher ambition level for 2030 was chosen to match the high estimate from the NAPCP dataset. Looking beyond 2030 two 2040+ scenarios were designed to explore potential regulatory measures for larger dairy and beef farms and planting optimised shelter belts downwind of livestock houses and manure storage facilities, for recapturing ammonia emissions from these emission sources. The 2040+ time horizon was chosen for the latter scenario to consider tree growth as such shelterbelts take time to become effective.

For NO_x measures two levels of ambition beyond meeting the NECR targets by 2030 were modelled: an additional 10% emission reduction in agglomerations classified as ‘urban areas’ by 2030 and a further 15% across all source sectors across the whole of the UK on top of this scenario for 2040+. Tables 2-2 and 2-3 provide a summary of the types and levels of ambition of measures across all scenarios, for both NH_3 and NO_x.

Table 2-2. List of selected scenarios taken forward for modelling under work package 3 of the Nitrogen Futures project, with short descriptions. All scenarios are described in detail in Annex 1 (baselines) and Annex 2 (mitigation scenarios).

Year	Short name	Description	No. of scenarios	Comments on selection
2017	Baseline	Best estimate of present time	1	NAEI 2017 with small updates where available)
2030	BAU (WM)	Business As Usual With Measures (WM) baseline (no spatial targeting)	1	2030 baseline (not meeting NECR); data provided by Defra
2030	NAPCP+DA (NECR NO_x)	UK-wide emission reductions – NAPCP+DA measures for NH_3 & no extra NO_x reduction beyond NECR target (no spatial targeting)	1	NOx: NECR target NH_3: NAPCP central estimate with DA medium ambitions; NAPCP data provided by Defra, modified with DA input for NH_3 as part of this project
2030	NAPCP+DA	UK-wide emission reductions – NAPCP+DA for NH_3 & -10 % for NO_x (targeted across agglomerations)	1	NH_3: as above, non-spatially targeted medium ambition for comparison against targeted scenarios NO_x: -10% across agglomerations, otherwise as NECR target

Year	Short name	Description	No. of scenarios	Comments on selection
2030	ERZ SAC 2km ERZ SSSI 1km ERZ SSSI 2km ERZ SSSI 5km	Spatially targeted emission reductions – high ambitions (maximum feasible) for NH_3 in ERZ around sites, outside ERZ: NAPCP+DA. -10 % NO_x reduction on baseline for agglomerations	4	Testing different widths of ERZ, mainly for SSSIs (as preferred by Steering Group), but with 1 SAC-based scenario to enable quantitative efficiency estimates for both types of sites
2030	High Ambition exc. Cattle	High ambitions for NH_3 everywhere (i.e. as for ERZ above, UK-wide); [excl. the additional more ambitious cattle measures described in the 2040+ scenario below]	1	To enable a fully quantitative comparison across the selected scenarios
2030	EDZ SSSI 1km	Spatially targeted displacement of NH_3 emissions around designated sites, with NAPCP+DA for NH_3, & 10 % reduction in NO_x emissions	1	EDZ can also represent land use de-intensification, but modelled here as moving of slurry/manure spreading away from designated sites
2040+	High Ambition inc cattle	UK-wide emission reductions - high ambitions for NH_3 (*inc. higher ambitions for cattle*) & additional 15 % reduction in overall NO_x emissions compared with NAPCP+DA	1	Useful for understanding what overall highest ambition everywhere for 2040+ could achieve, inc. possible additional measures for larger beef (>100 cows) and dairy (>150 cows) farms
2040+	ERZ SSSI 2km inc cattle	Spatially targeted emission reductions – high ambitions (maximum feasible + cattle ambitions) for NH_3 emissions around SSSIs/ASSIs, elsewhere NAPCP+DA; additional 15 % reduction in NO_x emissions compared with NAPCP+DA;	1	2 km zone preferred to other ERZ widths for testing
2040+	Trees SSSI 2km	Tree planting surrounding emission sources in addition to UK-wide NH_3 emission reductions (NAPCP+DA) & additional 15 % reduction in NO_x emissions compared with NAPCP+DA	1	Model shelter belt effect for all livestock housing and manure storage facilities for cattle, pigs & poultry, but not sheep, horses, goats and farmed deer (uptake 75-80%); for 2 km zone around SSSIs
2030	CLe opt. ERZ (no urea) CL opt. ERZ (no urea)	Optimised spatial targeting with efficient combinations of measures (based on 1st round of modelling); optimised minimum ERZ widths, combined with 1 km EDZ and replacing all urea/UAN fertiliser with lower emission alternatives	2	Critical Level (CLe) targets easier to achieve than Critical Loads (CL), as concentrations tail off faster; long-range transport influences N deposition and therefore CL exceedance more;

Table 2-3. Summary description of baseline and mitigation scenarios modelled for 2017, 2030, 2040+. ERZ are spatially targeted Emission Reduction Zones around designated sites, and EDZ Emission Displacement Zones (see Table 2 for more details and Nitrogen Futures Annex 2 for fully detailed scenario definitions). Cattle reg. refers to additional regulatory measures for larger cattle farms, agglom. refers to agglomerations, i.e. large urban areas used by Defra to report air quality. BAU refers to Business As Usual and NAPCP is the National Air Pollution Control Programme, with modifications by the Devolved Administrations (DA) - see Annex 1 for detailed descriptions of the 2030 baseline scenarios.

Short scenario names	year	NH_3 spatially targeted?	NH3 ambition within ERZ	NH3 ambition outside ERZ	NH_3 EDZ	NH_3 Trees	urea/UAN replacement	NO_x measures
2017 Baseline	2017	UK-wide	-	-	-	-	-	baseline
2030 BAU (WM)	2030	UK-wide	BAU	BAU	-	-	-	BAU (WM)
2030 NAPCP+DA (NECR NOx)	2030	UK-wide	NAPCP+DA	NAPCP+DA	-	-	-	NECR
2030 NAPCP+DA	2030	UK-wide	NAPCP+DA	NAPCP+DA	-	-	-	NECR -10% in agglom.
2030 ERZ SAC 2km	2030	2 km	high scenario	NAPCP+DA	-	-	-	NECR -10% in agglom.
2030 ERZ SSSI 1km	2030	1 km	high scenario	NAPCP+DA	-	-	-	NECR -10% in agglom.
2030 ERZ SSSI 2km	2030	2 km	high scenario	NAPCP+DA	-	-	-	NECR -10% in agglom.
2030 ERZ SSSI 5km	2030	5 km	high scenario	NAPCP+DA	-	-	-	NECR -10% in agglom.
2030 High Amb. exc. cattle	2030	UK-wide	high scenario	high scenario	-	-	-	NECR -10% in agglom.
2030 EDZ SSSI 1km	2030	1 km	NAPCP+DA	NAPCP+DA	y	-	-	NECR -10% in agglom.
2040+ High Amb. inc. cattle	2040+	UK-wide	high + cattle reg.	high + cattle reg.	-	-	-	NECR -10% & addit. -15%
2040+ ERZ SSSI 2km inc. cattle	2040+	2 km	high + cattle reg.	NAPCP+DA	-	-	-	NECR -10% & addit. -15%
2040+ Trees SSSI 2km	2040+	2 km	NAPCP+DA	NAPCP+DA	-	y	-	NECR -10% & addit. -15%
2030 CLe opt. ERZ SSSI (no urea)	2030	variable	high scenario	NAPCP+DA	y	-	y	NECR -10% in agglom.
2030 CL opt. ERZ SSSI (no urea)	2030	variable	high scenario	NAPCP+DA	y	-	y	NECR -10% in agglom.

2.4 National scale modelling (UK & countries)

The modelling framework used joins together UK high-resolution capability for emissions and projections, atmospheric concentrations and deposition, and effects assessment metrics (Figure 2-2). The individual components of the modelling framework are introduced below and described in more detail in subsequent sections.

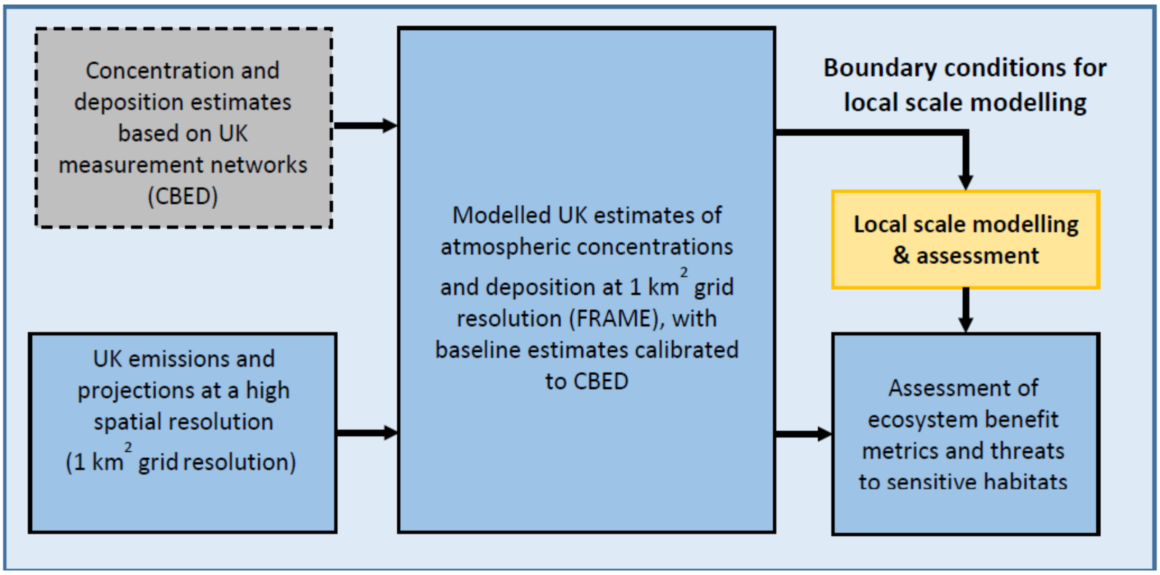

Figure 2-2. Overview of modelling framework used for UK high-resolution scenario modelling, including FRAME (Fine Resolution Atmospheric Multi-pollutant Exchange) and CBED (Concentration-Based Estimated Deposition) models.

- The new version of the detailed agricultural emission inventory model (coded in C#) is not suited to running scenarios, with many hundreds of input parameters required and

long run times. For this project, therefore, a simplified spreadsheet version of the model was developed based on the existing NARSES spreadsheet model (Webb & Misselbrook 2004; Misselbrook *et al.* 2004). Activity data and parameter values were updated for this project. This simpler model gives an output for each agricultural sector which is consistent with the official inventory model at the country level. There is only a small residual difference between the detailed and simplified versions of the model, of 0.13 kt NH_3 at the UK level, which represents 0.1% of the estimated total for 2030.
- The high-resolution modelling system for agricultural NH_3 emissions is part of the UK's agricultural emission inventory which provides the annual emission maps freely available from the NAEI[10] (under Defra project SCF0107, Carnell *et al*. 2019b). This model, AENEID (Atmospheric Emissions for National Environmental Impacts Determination; Dragosits *et al.* 1998; Hellsten *et al.* 2008), creates non-disclosive 1 km grid emission maps (Carnell *et al.* 2019b). The model is fully compatible with the wider agricultural emission model under Defra project SCF0107 for implementing scenarios, as well as the simpler NARSES spreadsheet model. AENEID was also used under the predecessor project on spatial targeting (Defra AC0109) to implement scenarios of several spatially targeted mitigation scenarios developed for designated sites (Dragosits *et al*. 2014).
- The UK FRAME model (Dore *et al.* 2007; Fournier *et al.* 2004; Singles *et al.* 1998; Vieno *et al.* 2010; Fine Resolution Atmospheric Multi-pollutant Exchange) is currently used to derive high-resolution atmospheric concentrations (NH_3, NO_x, SO_2) and N deposition data for future scenario assessment under a number of Defra and agency projects. It benefits from both high 1 km resolution as well as a fast run time allowing multiple scenarios to be rapidly calculated. The high-resolution UK modelling required the wider boundary conditions to be modelled for Europe, to account for import of pollution into the UK domain for 2030.
- NH_3 concentrations calculated with FRAME are calibrated against the National Ammonia Monitoring Network (NAMN), developed and operated by UKCEH, for calculation of exceedance of the NH_3 critical level. The median bias in the model-measurement comparison was used to bring modelled concentrations in line with measured values. For NO_2 concentrations, calibration to PCM (Pollution Climate Model, Brookes *et al.* 2019) was carried out.
- The system used to calculate S and N deposition and the exceedance of critical loads over recent and historic years for official Defra purposes employs the CBED (Concentration Based Estimated Deposition) inferential model (Smith *et al.* 2000). The inferential modelling approach differs fundamentally from an atmospheric chemistry transport model, such as FRAME, as it relies on measurements from the UKEAP Eutrophying and Acidifying Pollutants monitoring network and interpolation techniques. Deposition data for emission scenarios calculated with the FRAME model are therefore calibrated relative to CBED deposition (Smith *et al.* 2000) such that the simulated reduction in deposition is consistent with the official estimates. Previously, e.g. under Defra AC0109, it was not possible to calibrate the modelled deposition output on a 1 km grid due to the restriction of the 5 km CBED resolution. However, UKCEH recently developed a 1 km calibration approach for N deposition which was available for use under this project. This enabled retaining the high resolution of the FRAME model simulations whilst ensuring deposition data is normalised to the CBED estimates at a 1 km resolution.
- The UK National Focal Centre's (UKCEH Bangor, Defra project AQ0843, Rowe *et al.* 2019) well-established methodology for assessing effects of atmospheric N on vegetation, through critical loads and critical levels exceedance, was used for quantifying environmental benefits of the scenarios developed under this project. The methodology provides a comprehensive set of statistics at the UK, DA, habitat and designated-sites level, including excess nitrogen deposition (AAE). The critical loads

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[10] See naei.beis.gov.uk.

and levels methodologies have been updated to a 1 km grid resolution for operational use. Other metrics used for assessing the scenarios are described in Section 2.2.

The high-resolution (1 km grid) modelling methodology described above was implemented for all scenarios (12 agreed with Steering Group, 15 completed). The following steps were followed for all scenarios:

1. Development of high-resolution emission maps (1 km by 1 km grid) for UK baseline and spatially targeted scenarios – using projections of activity data and emission projections for the range of future scenario measures and ambitions modelled under this project.
2. The FRAME model was run for 15 scenarios in total, using the emission maps prepared under Step 1, to produce concentration and deposition maps, with all model runs scaled relative to the calibrated 2017 baseline.
3. All scenario outputs were assessed against a set of metrics (agreed with the Steering Group), following a wide-ranging review of ecosystem benefit metrics described in Section 2.2.

For some more complex spatially targeted scenarios, i.e. the optimised variable width emission reduction zones (Section 3.4 and **Annex 4**), it was necessary to assess key metrics for the main batch of scenarios before the final optimised emission scenarios could be produced, run through the FRAME model, calibrated and assessed.

Following the completion of the model runs, the scenario outputs were analysed and interpreted as follows, for emissions, concentrations, deposition and effects:

- Comparison of current (2017) vs the 2030 baseline scenarios (BAU (WM), NAPCP+DA (NECR NO_x)) – this enabled an evaluation of the likely effects of currently active and planned NECR-related policies on atmospheric N inputs to sensitive vegetation.
- Comparison of 2030 NAPCP+DA (NECR NO_x) baseline with spatially targeted scenarios (for 2030 and/or beyond) – this enabled an evaluation of a) the potential of spatial targeting vs. UK-wide scenarios, b) the development of optimised mitigation scenarios for maximum ecosystem benefit, and c) testing different levels of ambition for mitigation.
- Separate quantification of benefits for each country and the UK (for sensitive vegetation, priority habitats and designated sites).
- Effects due to NH_3 and NO_x were analysed separately for atmospheric concentrations and N deposition. Each model run contains N deposition data split into oxidised (NO_x related) vs. reduced (NH_3 related) deposition, regardless of the scenario definition. Therefore, the relative contribution of reduced and oxidised N to total N deposition can be determined for all scenarios.
- *Interpretation of spatial patterns in terms of reduced emissions, concentrations, deposition and effects, relating to current and planned policies (where applicable to scenarios), as well as likely impact of optimised spatial planning scenarios.
- Results from the UK and country scale modelling are shown in Section 3, with further details in **Annex 4**. An assessment of uncertainty in the model input and output, as well as limitations of the metrics applied is given in Section 4.
- Through the UK-wide high-resolution (1 km grid) modelling and assessment, many of these outputs can be used for assessment at the scale of designated sites. The concentration and deposition data informed the local scale demonstration case studies, by providing materials for initial assessments as well as boundary conditions for nesting within the UK and country context, including long and medium-range transport input to the local study areas, from the wider region and internationally. Local information on agricultural practice, exact location of emission hotspots, road traffic statistics, *etc.*, was used, where available, for a fuller site assessment.

2.5 Local scale assessment and modelling (case studies)

Local demonstration studies aim to illustrate the spatial targeting concept through a range of activities, and across a variety of sites, across the DAs and geographically. This is to help tease out the variation of different policy ambitions at the local scale, and to enable the use the project's output for practical application. The approach taken was to assess a larger number of case studies through 15 illustrative local assessments of spatial targeting of measures. This approach enabled the case studies to encompass a wider variety of situations in terms of geography, emission sources, severity and type of atmospheric N input. For example, it is important to test whether sites that receive mostly long-range N deposition i.e. a high proportion of wet deposition, would not necessarily benefit from spatial targeting. By contrast, sites that have multiple or large local sources would benefit substantially from local measures compared with the same overall emission reductions being diluted over a wider area. The detailed local assessment, including methodology, and all site profiles can be found in **Annex 5** to this report.

2.5.1 Selection of representative case studies

To determine how effective spatial targeting of mitigation can be at a site level, it was important to choose appropriate case study sites for assessing local and national scale information. The aim was to include a wide range of habitats across different levels of severity of atmospheric N pollution threats, N pollution source types, and different geographical locations. In addition, it was important to include a number of sites where information from previous studies or local data were available. In summary, the sites were selected for a range of conditions based on the following criteria:

- Ammonia vs NO_x sources;
- Emission source sectors (agriculture, transport, *etc.*);
- Relatively clean sites vs those very heavily affected by atmospheric N input;
- Sites mainly affected by local sources vs those mainly affected by long range N deposition;
- Habitat types (e.g. bogs, woodland, heath, grassland types);
- Primary vs secondary mitigation (i.e. emission reduction vs recapture); and
- Geography - covering:
    - all parts of the UK (England, Wales, Scotland, Northern Ireland); and
    - upland & lowland, urban vs rural vs very remote.

The site selection process involved detailed consultation with the project Steering Group, with 15 sites being chosen. These are characterised in Table 2-3.

Table 2-3. Case study sites selected for local assessment of spatial targeting.

#	Site	Country	Main reasons for selection
1	Ashdown Forest	England	Transport/ combustion & other sources of atmospheric N input (NO_x, NH_3)
2 3	Breckland (2 sites, Farmland & Forest)	England	Various agricultural sources (pigs, poultry, arable) (mainly NH_3)
4	Epping Forest	England	Transport/ combustion (NO_x, NH_3)
5	Fenn's, Whixall, Bettisfield, Wem & Cadney Mosses	Wales & England	Various agricultural sources (cattle, poultry) (mainly NH_3)
6	Dinefwr Estate	Wales	Local agricultural NH_3 emissions; elevated concentrations affecting sensitive lichen communities
7	Gregynog	Wales	Poultry farms (mainly below PPC limit) (mainly NH_3); elevated concentrations affecting sensitive lichen communities
8	Beinn Dearg	Scotland	One of the cleanest sites in Scotland with low NH_3 concentrations & N deposition
9	Glasgow Low Emission Zone (LEZ)	Scotland	Not a designated site but of interest to Scottish Government; transport/ combustion sources of NO_x and NH_3
10	Whim Bog	Scotland	Adjacent poultry farming, small contributions from extensive beef and sheep farms (mainly NH_3)
11 12	Ballynahone Bog & Curran Bog	NI	Intensive mixed farming landscape, with dairy, beef, pig and poultry farming (mainly NH_3)
13	Lough Navar Scarps & Lakes	NI	Relatively clean site within Lough Navar forest (medium/ long range)
14	Peatlands Park	NI	Intensive mixed farming landscape (mainly NH_3)
15	Turmennan	NI	Intensive mixed farming landscape, at least 1 IED farm <2km (mainly NH_3)

2.5.2 Case studies in the context of national scale modelling

The use of 1 km grid concentration and deposition maps produced for scenario assessment in this project marks a significant improvement to the previous Defra AC0109 project (Ammonia Future Patterns, Dragosits *et al.* 2014) which was based on 5 km grid resolution modelling. Local scale assessments also demonstrate the importance of more detailed data, beyond the 1 km grid national scale modelling carried out, for quantifying impacts on sensitive habitats and sites. This was explored for the selected case study sites and illustrated in the individual assessments of sites (see **Annex 5** for details). For some types of sites or types of atmospheric N input, national scale modelling alone is appropriate. For other sites, further local scale emission data and modelling is helpful to further assess the suitability and ambition of potential mitigation strategies. For the case studies assessed here, this was especially the case for sites where local emissions may be a large contributor to N deposition.

2.5.3 Modelling and assessment methodology

Existing information on the sites' designated features, their critical loads, source attribution data (Bealey & Dore 2017), agricultural emission density, the 1 km grid scenario outputs and visual assessment using satellite images were collated and assessed for all case studies (see **Annex 5** for details). Further information was included where available, e.g. atmospheric concentration measurements, existing case study reports and project reports from a wide range of sources (Carnell & Dragosits 2015, 2017; Natural England 2015; Vogt *et al.* 2013), and an ongoing/unpublished work for NIEA in Northern Ireland (Y.S. Tang, U. Dragosits, I. Thomas, UKCEH, pers. comm.).

For sites affected by road transport (Epping Forest, Ashdown Forest, Peatlands Park, Glasgow LEZ), additional local scale modelling and re-analysis of published model results was carried out as part of the local assessment of case studies (see **Annex 5** for details).

For three case studies and relevant habitats within them, selected scenario outcomes were run through the Factor 1 Exceedance scores of the Nitrogen Decision Framework (Jones *et al.* 2016). This was important to understand how this metric of ecological risk changed under scenarios to reduce emissions and with improved estimates of N deposition at the site level.

3 Results, implications and recommendations for optimisation of benefits

3.1 UK and country scale

The following sections provide a summary of the detailed results from the UK- and country-scale high-resolution scenario modelling presented in **Annex 4**. The results are presented for three main strands of scenario analysis for atmospheric N emissions, concentrations, deposition and ecosystem effects. Projected change from present (2017 data) to 2030, using best available data for currently known baselines and planned strategies (Section 3.1.1);

- Potential future mitigation strategies for 2030 and 2040+, with measures tested UK-wide or spatially targeted close to N-sensitive designated sites (Sections 3.1.2-3.1.4); and
- Testing all scenarios against the UK Government's CAS target for 2030, i.e. a 17% decrease of *total reactive N deposition onto protected, priority, sensitive habitats* (Section 3.1.5).

3.1.1 Projected change in atmospheric emissions, concentrations, deposition and ecosystem effects under baseline and planned strategies to 2030

NH_3 Emissions

Ammonia emission reductions for the 2017 and 2030 baseline scenarios are summarised in Table 3-1. The results show an overall increase in emissions between 2017 and 2030 BAU (WM), by 1%. Emissions from cattle, sheep and N fertilisers under 2030 BAU (WM) are projected to decline by 3, 6 and 3%, respectively, compared with the 2017 baseline. UK poultry and pig emissions are both projected to increase by 3%. There is also a notable increase in non-agricultural emissions, largely linked to anaerobic digestion. Projected emission trends are directly related to trends in projected livestock numbers, as under the 2030 BAU (WM) scenario there are no changes to the current 2017 values for emission factors and very little change in terms of implementation of mitigation measures. The exception to this is for dairy cows, where projected increase in milk yield per cow results in an increase in the implied emission factor per cow, but the impact of this on total emissions is offset by a reduction in the number of dairy cows. This is due to higher N excretion rates per animal, which are associated with the higher productivity. For other livestock types, we have no robust projections for productivity (and hence N excretion) changes, but direction of change, if any, would likely be for lower N excretion per animal associated with improved genetic merit and more efficient utilisation of dietary protein. Emissions from fertiliser use are associated with overall quantity of N use but also the proportion of different fertiliser types. Urea, in particular, is associated with a higher emission factor than other N fertiliser types. We used FAPRI data to estimate future total N use, but lacking any detail, we have assumed the proportional use of different fertiliser types to remain at 2017 values. With the additional measures developed under the 2030 NAPCP+DA baseline, agricultural emissions are substantially reduced, by 38.4 kt (12% from 2017). For this baseline scenario, the largest absolute and relative emission reductions are predicted for cattle and mineral fertiliser.

Table 3-1. Comparison of UK ammonia emission totals for 2017 and 2030 baseline scenarios, by major sectors, with comparisons relative to 2017 baseline. N.B. 2017 emission totals include emissions from all sources that have been quantified, i.e. all sources that are relevant for an as complete as possible picture to explain concentration and deposition patterns. This includes "memo items" from the NAEI, i.e. emission sources that are not included in the official national totals, which are used for comparing against targets. For NH_3, this includes emissions from wild mammals and seabirds, as well as small amount from international shipping. "NECR NOx" refers to the NOx emissions meeting the 2030 NECR targets, with the NH_3 targets being slightly different from NECR/NAPCP, due to the DA modifications applied following consultation with the DAs.

	2017	2030 BAU (WM)		2030 NAPCP+DA (NECR NOx)	
Scenario	Baseline (kt NH_3)	kt NH_3	% difference to 2017	kt NH_3	% difference to 2017
Cattle	115.8	112.3	-3%	94.9	-18%
Sheep	9.6	9.0	-6%	9.0	-6%
Pigs	18.6	19.1	3%	17.1	-8%
Poultry	37.7	38.8	3%	34.6	-8%
Mineral fertiliser	44.9	43.5	-3%	28.7	-36%
Horses, Goats & Deer	1.4	1.4	0%	1.4	0%
Non-Agric. emissions[11]	61.4	67.9	11%	67.9	11%
Total	289.3	292	1%	253.6	-12%

Within the UK, there are some differences between the UK countries (Figure 3-1), with trends for England being much the same as for the UK, whereas Wales shows less of a decrease in emissions from cattle (0.4%) but a much larger decrease in emissions from sheep (by 12%). The modelled results for Scotland show larger decreases for cattle (4%) and N fertilisers (4%) but larger increases for poultry (3%) and pigs (15%). Northern Ireland also shows a larger decrease for cattle (5%) and N fertilisers (5%), a decrease for pigs (-7%) and an increase for poultry (3.5%). Total emissions from agriculture are projected to decrease by 1.7% for the UK and 1, 2, 2 and 4% for England, Wales, Scotland and Northern Ireland, respectively[12].

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[11] UK totals do not take account of the alternative traffic projections considered for local case studies in Annex 5.

[12] Totals do not include emissions from sewage sludge or digestate applications to land, which are not included in the NARSES modelling for agricultural sources. These sources are accounted for separately within the wider modelling framework used in this project.

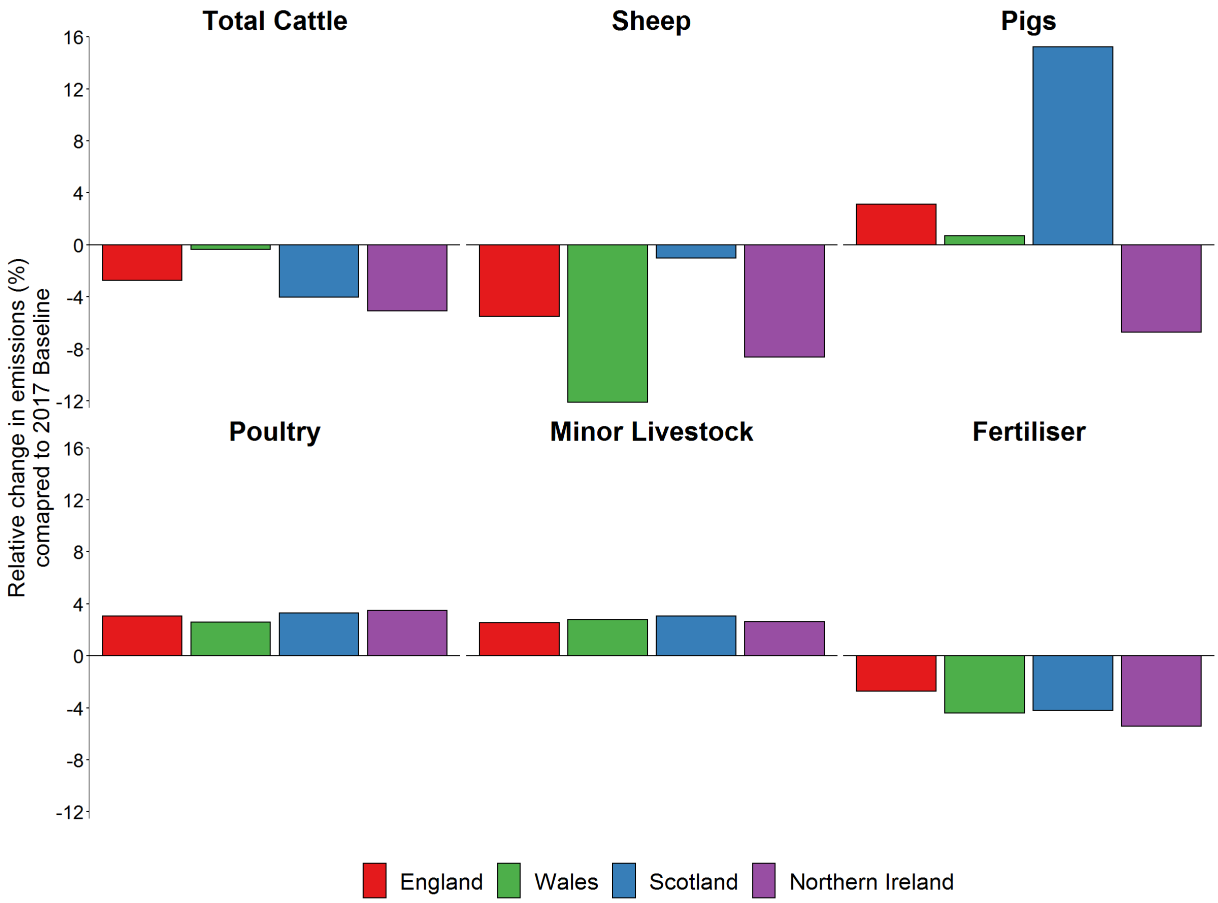


Figure 3-1. Relative change in agricultural emissions between 2030 BAU (WM) and 2017 baseline, emissions are separated by sector and presented individually for the UK countries (i.e. England, Wales, Scotland and Northern Ireland).

In terms of spatial distribution, the differentiation of mitigation by source sector plays a major role in determining where emission decreases are expected or, conversely where emission increases are expected. The local and regional spatial differences within each of the UK countries between the 2017 and 2030 BAU (WM) baselines are due to the assumptions made about the different agricultural livestock sectors and their spatial distribution (Figure 3-2). For example, despite mitigation measures, emissions from the pig and poultry sectors are estimated to increase between these two scenarios UK-wide, as these sectors are predicted to grow between 2017 and 2030. While overall spatial patterns of activity are expected to remain similar to the present over the next decade, individual sources such as farming enterprises, landfill or anaerobic digestion sites are likely to change dynamically over time, with some closing/reducing activities, and others newly opening or expanding. As it is not possible to predict the locations where such additional sector activities are likely to emerge, the assumption made was that emissions within each sector, by country rather than UK-wide, would increase/decrease proportionally. This results in the patchwork of small increases and decreases across the difference map. By contrast, the more ambitious measures modelled under the 2030 NAPCP+DA baseline result mostly in emission reductions throughout the agricultural sectors. There are some exceptions, and these are linked to high local densities of sectors that are predicted to increase at a country-scale.

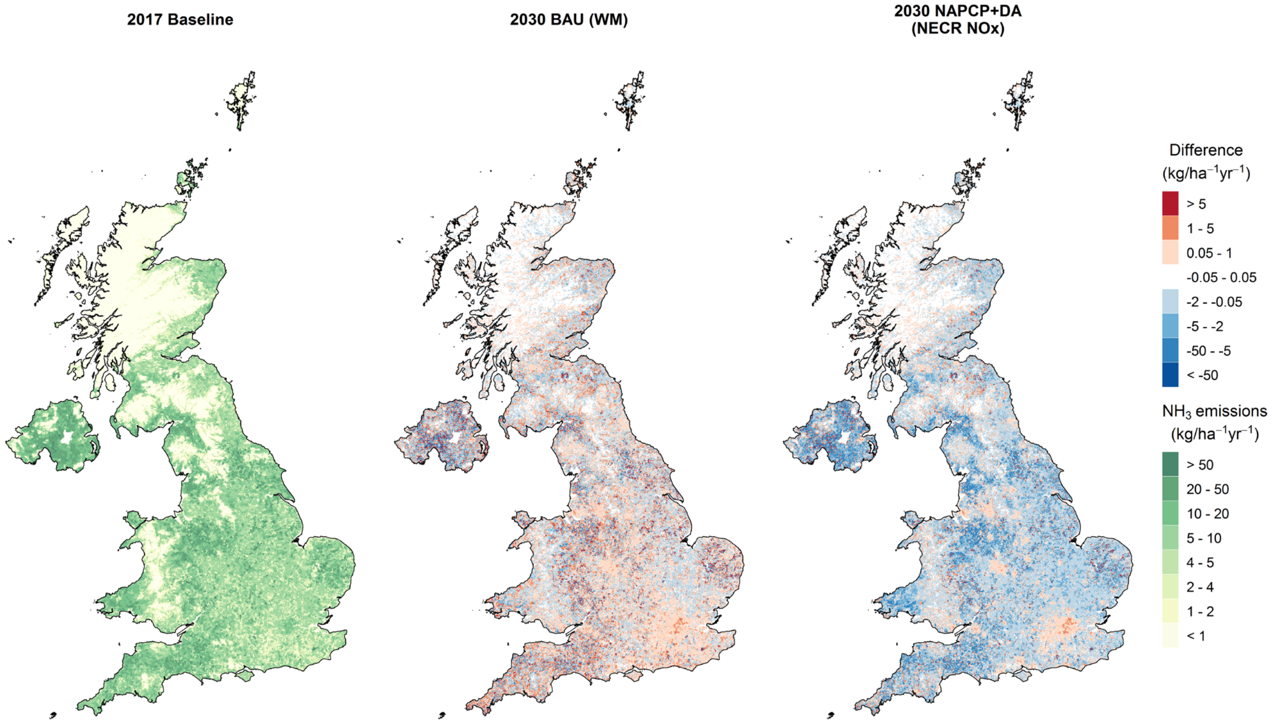


Figure 3-2. Comparison of NH_3 emission baselines: 2017, 2030 BAU (WM) and 2030 NAPCP+DA.

NO_x Emissions

For NO_x, the NECR targets (2030 NAPCP+DA (NECR NOx) are relatively more ambitious than for NH_3, with emissions due to almost halve, from 1,012 kt to 563 kt NO_2. The largest projected decreases are attributed to road transport, other transport (e.g. rail, airports, shipping), and energy production, with smaller decreases from other sectors (Table 3-2, Figure 3-3). A large part of the emission reductions needed for meeting the NECR target is already included in the 2030 BAU (WM) baseline, achieving a decrease in emissions by 348 kt NO_2.

Table 3-2. UK NO_x emission totals for the baseline scenarios, by major sectors. N.B. 2017 emission totals include emissions from all sources that have been quantified, i.e. all sources that are relevant for an as complete as possible picture for concentration and deposition patterns. This includes “memo items” from the NAEI, i.e. emission sources that are not included in the official national totals, which are used for comparing against targets. For NO_x, this includes international shipping, cropped to the model domain making up the difference to the total reported in the NAEI (as reported in 2019, 873 kt NO_2).

Scenario	**2017 Baseline**	**2030 BAU (WM)**	**2030 NAPCP+DA (NECR NOx)**
Energy Production	176.4	123.0	104.4
Domestic Combustion	60.5	58.6	49.8
Industrial Combustion	128.5	119.8	101.6
Industrial Processes	0.3	0.3	0.3
Fossil Fuel Extraction	0.1	0.1	0.1
Solvents	0.1	0.0	0.0
Road Transport	281.5	107.2	91.0
Other Transport	334.9	232.8	197.5
Waste	0.9	0.8	0.7
Agriculture	26.9	19.3	16.4
Other	1.5	1.5	1.3
Total	*1011.7*	*663.5*	*562.9*

For NO_x, the local and regional spatial differences are due to the assumptions that were made about the different sectors and their spatial distribution. While it was possible to take account of specific geographic differences (such as projected individual airport growth rates, power station data – see **Annex 1** for further details), other sectors had to be scaled using the overall predicted change across the UK. For example, industrial production or power generation sites are likely to change dynamically over time, with some sites closing, others newly opening or expanding. It was not possible to take account of such uncertain factors, in the same way as for ammonia.

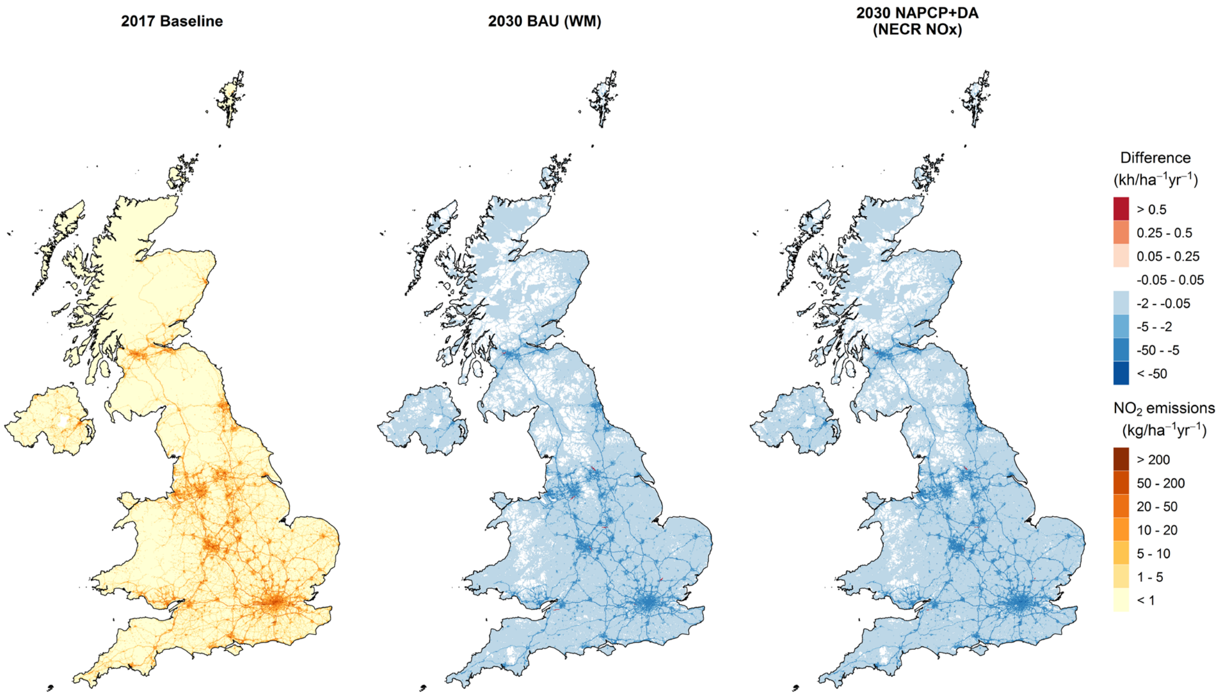


Figure 3-3. Comparison of NOx emission baselines: 2017, 2030 BAU (WM) and 2030 NAPCP+DA. N.B. The relevant detailed atmospheric concentration, deposition maps and further statistics are provided in **Annex 4**.

Atmospheric concentrations of NH_3 and NO_x

Atmospheric concentrations of ammonia (NH_3) and oxides of nitrogen (NO_x) were estimated for all scenarios by running the FRAME model with the spatially resolved emission estimates shown above (Figures 3-2, 3-3) followed by calibration with measurement data for the 2017 baseline. The methodology is described in detail in **Annex 4**.

Results show that baseline atmospheric NH_3 concentrations between 2017 and 2030 BAU (WM) are not estimated to change much and correspond closely with the underlying emission maps. Local increases and decreases mirror emission patterns which are based on emission projections for source sectors (Figure 3-4, NH_3 emissions shown in Figure 3-1 above). Larger NH_3 concentration differences, mostly decreases, were estimated between the most recent present-day estimate (2017) and the 2030 NAPCP+DA baseline. A comparison of baseline concentrations of NO_2 between 2017 and 2030 BAU (WM) shows substantial differences. The model results show further NO_2 concentration differences, mainly in the form of decreases, between the 2017 and the 2030 NAPCP+DA (NECR NO_x) baselines. This is due to projected/modelled reductions in emissions, as highlighted by the underlying emissions maps (Figure 3-3).

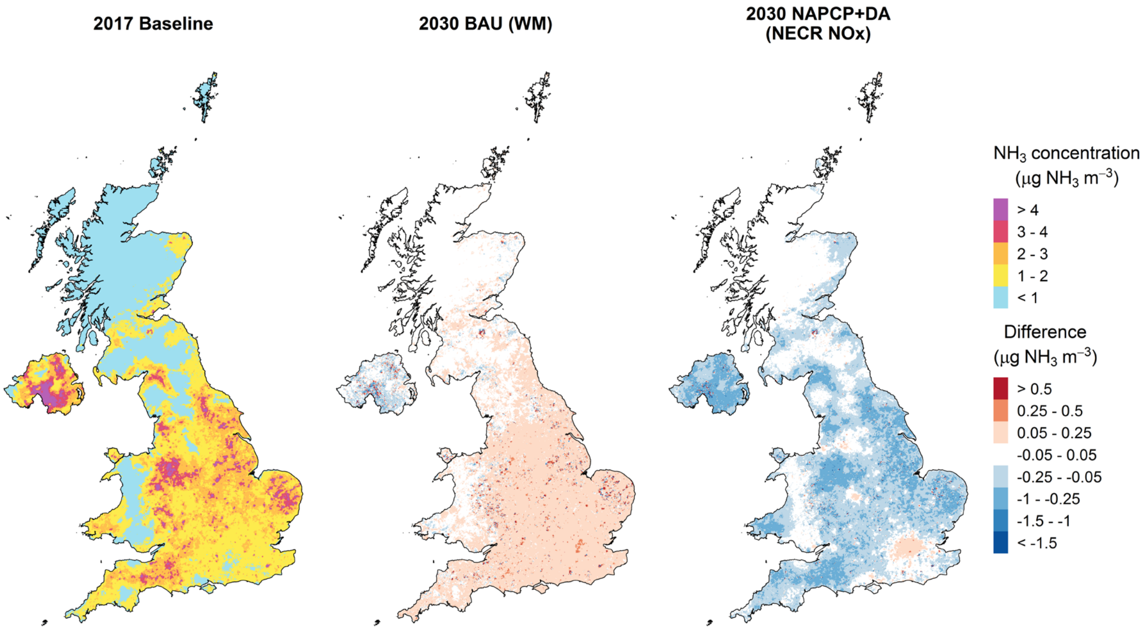


Figure 3-4. Ammonia concentration baselines: 2017 (left), difference to 2030 BAU (WM) (middle), difference to 2030 NAPCP+DA.

Atmospheric N deposition

N deposition is expected to decrease substantially between 2017 and both 2030 baseline scenarios, under existing emission reduction commitments, from 277.1 kt N in 2017 to 239.5 kt N under 2030 BAU (WM) and 219.1 kt N under 2030 NAPCP+DA (NECR NO_x) (Table 3-3). The 2030 BAU (WM) and NAPCP+DA (NECR NO_x) emission baselines are estimated to result in N deposition reductions across the UK overall of ~38 and ~58 kt N, respectively. Decreases in NO_x emissions are estimated to provide a larger part of the reductions in N deposition by 2030 (meeting NECR targets) of 35.6 kt N, with NH_x emissions contributing 22.2 kt N. Decreases in transboundary air pollution contribute to some of the improvements between 2017 and 2030 with lower imported N deposition estimated from Europe and beyond (c.12% lower NH_x-N imports and c.20% lower NO_y-N imports in 2030 NECR than 2017). This is due to the wide-ranging international efforts under the NECD and Gothenburg Protocol.

Table 3-3. Summary of N deposition to the UK land area for the 2017 and 2030 baseline scenarios, split into the main components of wet, dry, reduced and oxidised nitrogen (kt N). The data represent grid square average N deposition, i.e. the land cover within each model grid square is taken into account to provide land cover dependent total deposition.

Scenario (all values kt N)	**NHx-N dry**	**NHx-N wet**	**NOy-N dry**	**NOy-N wet**	**Total N**
2017 Baseline	75.3	93.8	34.6	73.3	277.1
2030 Baseline BAU (WM)	76.1	86.5	22.8	54.1	239.5
2030 Baseline NAPCP+DA (NECR NOx)	67.2	79.7	20.9	51.4	219.1

Substantial differences in N deposition to low-growing semi-natural vegetation are expected for the 2030 NAPCP+DA baseline scenario, with decreases of up to 5 kg N ha^{-1} yr^{-1} across most of England and Northern Ireland compared with the 2017 baseline (Figure 3-5). Similar spatial patterns are also estimated for deposition to woodland features, with higher reductions estimated across large parts of England and Northern Ireland (see **Annex 4**).

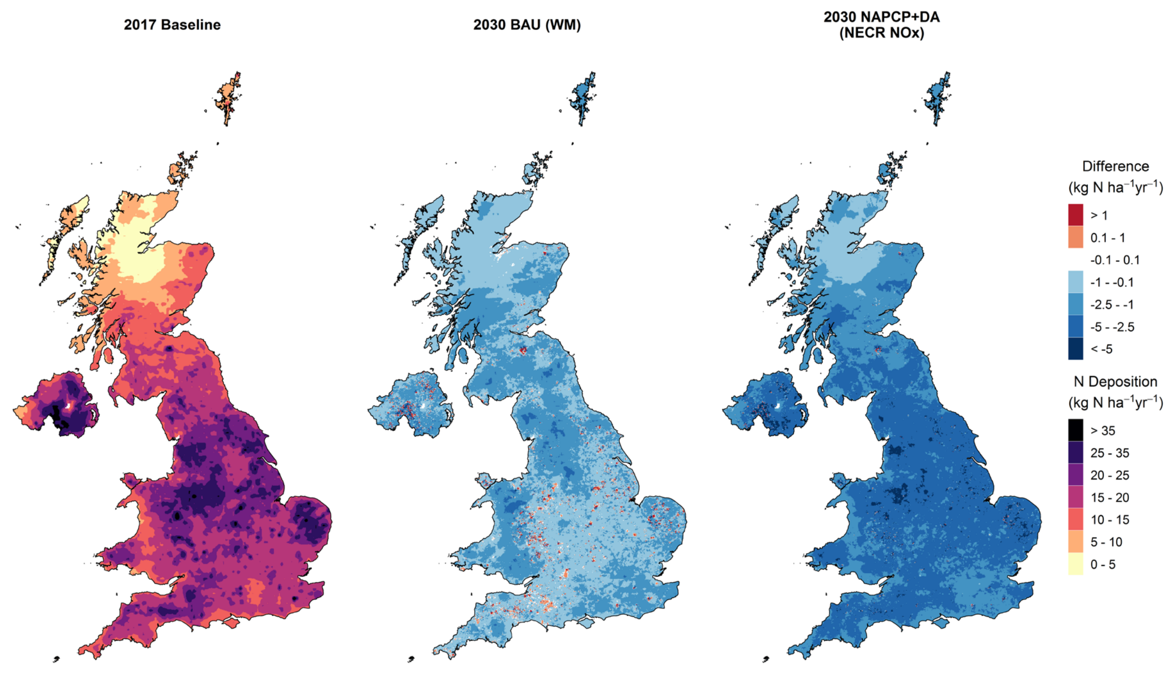


Figure 3-5. N deposition to low-growing semi-natural vegetation features - baselines: 2017 (left), difference to 2030 BAU (WM) (middle), difference to 2030 NAPCP+DA.

Ammonia critical levels exceedance

The substantial emission reductions under the 2030 NAPCP+DA baseline scenario results in 106 sites expected to no longer exceed the 1 µg NH_3 m^{-3} critical level and 135 sites to no longer exceed the 3 µg NH_3 m^{-3} critical level (Table 3-4).

Table 3-4. Number of nitrogen sensitive UK SSSIs that are in exceedance of 1 and 3 µg NH_3 m^{-3} critical levels (CLe) under each of the baseline emission scenarios. The 1 µg m^{-3} critical level is relevant for assessing lichens, mosses and bryophytes and the 3 µg $NH_3 m^{-3}$ for assessing higher plants. Exceedance of CLe was assessed based on the maximum estimated concentrations at sites.

Scenario	Critical level (ug NH_3 m^{-3})	England	Wales	Scotland	Northern Ireland	UK
Number of SSSIs	-	2979	732	930	240	4853
2017 Baseline	1	2678	481	216	217	3567
2030 BAU (WM)		2755	507	242	211	3690
2030 NAPCP+DA (NECR NOx)		2633	457	191	205	3461
2017 Baseline	3	278	26	9	55	361
2030 BAU (WM)		314	29	8	48	392
2030 NAPCP+DA (NECR NOx)		173	14	7	38	226

Differences in exceedance of the 1 and 3 µg NH_3 m^{-3} CLe at nitrogen sensitive sites between the 2017 and 2030 baselines, are shown in Figure 3-6. The spatial distribution of sites no longer in exceedance (blue dots) reflects the patterns and gradients across the UK NH_3 concentration maps. Generally cleaner sites away from major emission source areas, in the uplands and closer to coasts (Northern England, Wales, western NI and southern Scotland) improvements in the number of sites no longer in exceedance of the 1 µg NH_3 m^{-3} CLe. By contrast, improvements in the number of sites no longer in exceeding the 3 µg NH_3 m^{-3} CLe are located mainly in agricultural landscapes with relatively higher emission densities, i.e. English lowland areas and large parts of Northern Ireland. There are small numbers of SSSIs in both maps in Figure 3-6 that are estimated to exceed their critical levels in the future (red dots) – this is due to the predicted increases in the projection of specific emission source sectors (Section 3.1.1, Table 3-1).

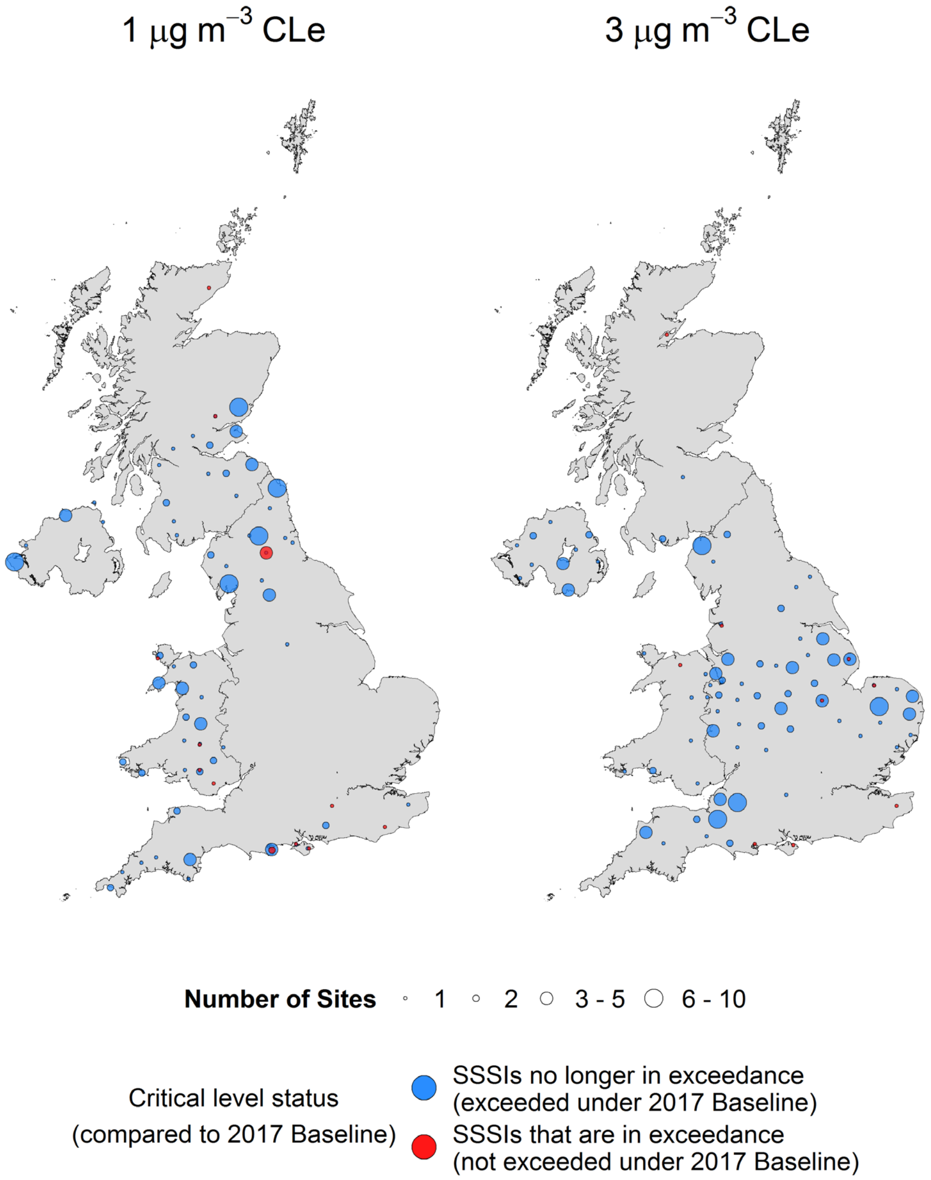


Figure 3-6. Maps showing the additional number of nitrogen sensitive UK SSSIs (compared with the 2017 baseline) that are no longer in exceedance of the 1 µg m^{-3} (left map) and 3 µg m^{-3} (right map) critical levels under the 2030 NAPCP+DA baseline scenarios. Red dots show sites (or clusters of sites) that are newly in exceedance, compared with the 2017 baseline. The 1 µg m^{-3} critical level is relevant for assessing lichens, mosses and bryophytes. Exceedance of critical levels has been assessed based on the maximum estimated concentrations at sites. Sites clustered together with nearby sites up to a distance of 50 km for visualisation.

Critical Loads exceedance

Differences in the number of nitrogen sensitive UK SSSIs that are in exceedance of critical loads (CL) between the 2017 and 2030 NAPCP+DA baselines are presented in Table 3-5 and Figure 3-7.

Table 3-5: Number of nitrogen sensitive UK SSSIs that are in exceedance of nutrient critical loads under each mitigation scenario (DWI), values in brackets show overall change compared with the 2017 baseline. The figures exclude the 127 SSSIs where critical load information is unknown.

	England	Wales	Scotland	Northern Ireland	UK
Number of SSSIs	2979	732	930	240	4853
Number of SSSIs with CLs	2960	679	928	188	4853
2017 Baseline	2647	668	678	172	4165
2030 BAU (WM)	2608 (- 39)	664 (- 4)	639 (- 39)	171 (- 1)	4082 (- 83)
2030 NAPCP+DA (NECR NOx)	2468 (- 179)	659 (- 9)	594 (- 84)	168 (- 4)	3889 (- 276)

In comparison to the 2017 baseline, many additional N-sensitive UK SSSIs are projected to no longer exceed their critical loads under both the 2030 BAU (WM) and 2030 NAPCP+DA scenarios. Decreases in N deposition in the 2030 BAU (WM) scenario are mainly due to a combination of UK NO_x emission decreases and decreases in long-range atmospheric N import from the continental Europe and the Republic of Ireland (not shown here, see **Annex 4** for details). Substantial further decreases in CL exceedance are estimated under the 2030 NAPCP+DA (NECR NO_x) baseline scenario compared with 2030 BAU (WM). The additional sites no longer exceeding their CLs under 2030 NAPCP+DA (NECR NO_x) are in emission source areas as well as more remote parts of the UK, illustrating that different deposition pathways are contributing across the UK, i.e. both local and long-range.

Overall, an additional 276 SSSIs are estimated to no longer exceed their critical loads (for all designated features present) in the 2030 NAPCP+DA (NECR NO_x) baseline scenario, compared with 2017. Of these sites, 64% of these sites located in England, 31% in Scotland, 3% in Wales and >1% in Northern Ireland. It is important to note that decreases in N deposition are due to two main processes: firstly, local effects of mitigation, relating to the dry deposition of reduced N, and secondly, medium/long-range input of both oxidised and reduced nitrogen. The effects of mitigation across the scales of the two types of processes, short and long range, show therefore, different spatial patterns depending on the deposition component(s) dominating locally.

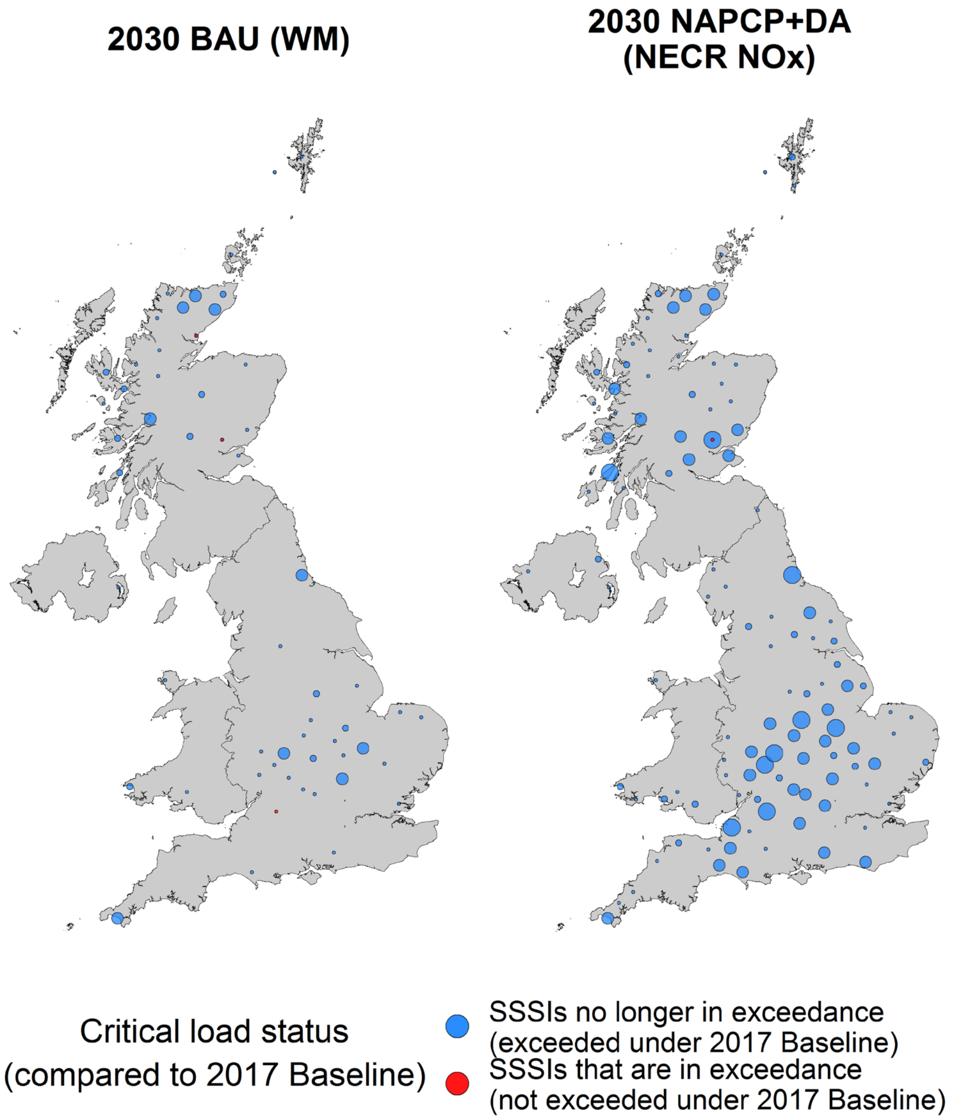


Figure 3-7. Maps showing the additional number of nitrogen sensitive UK SSSIs (compared with 2017 baseline) that are no longer in exceedance of critical loads under the two 2030 baseline scenarios. Red dots show sites (or clusters of sites) that are newly in exceedance, compared with the 2017 baseline. This figure excludes 127 SSSIs where critical load information is unknown. Sites are clustered together with nearby site up to a distance of 50 km for visualisation.

3.1.2 Future mitigation scenarios

This section describes modelled emissions, concentrations, deposition and ecosystem effects metrics for the mitigation scenarios developed for 2030 and 2040+. The scenarios include both UK-wide application of measures and spatially targeted options. Scenario results are also compared with the baseline scenarios for 2017 and 2030 described in detail in Section 3.1.1 above.

NH_3 Emissions

Agricultural NH_3 emission reductions for the mitigation scenarios are shown in Figure 3-8. The largest decreases from the 2030 NAPCP+DA baseline are, as expected, for UK-wide 2030 and 2040+ scenarios. As the spatially targeted scenarios are only applied to concentric zones of different widths surrounding designated sites (ERZ/EDZ), the equivalent measures provide much more modest emission decreases if summed up for the UK as a whole, or by country, compared to the UK-wide scenarios. For NH_3 emission sectors other than agriculture (i.e. waste, transport, industry, nature, *etc.*), no further mitigation measures were implemented beyond those already included in the 2030 NAPCP baseline assumptions (see **Annex 1**). This means that any changes in overall emission input data to the scenario modelling can be attributed to agricultural mitigation and interpreted more clearly throughout the model chain, i.e. atmospheric concentrations, deposition and vegetation effects metrics.

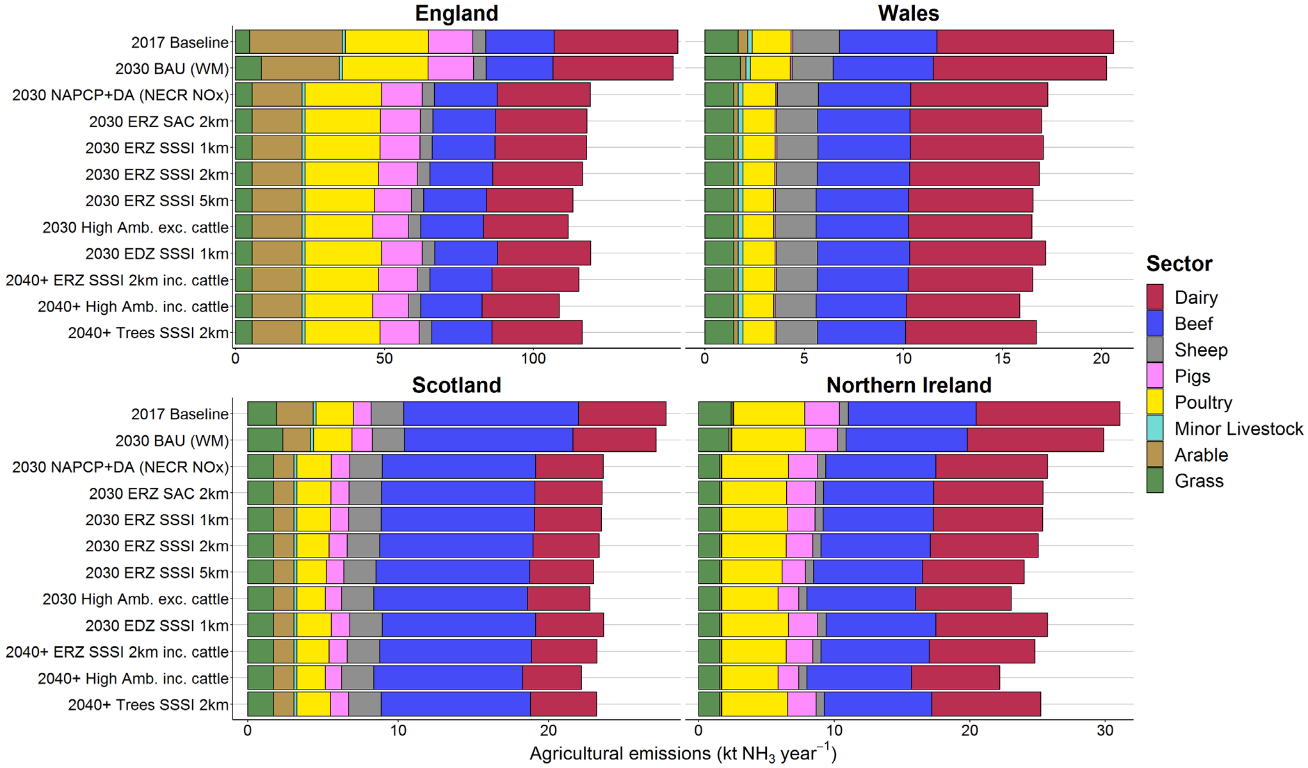


Figure 3-8. Comparison of scenarios results: agricultural NH_3 emissions totals for the UK and Devolved Administrations separated by agricultural emission sector.

Figure 3-9 illustrates the different emission reduction zones (ERZ) where spatially targeted NH_3 measures were modelled. The maps show the spatial distribution of the ERZs and illustrate the level of ambition of the different ERZ scenarios. It is evident from these maps that the larger zones equate to a considerable proportion of the UK's and Devolved Administrations, however, there are substantial areas that are at least 2 or 5 km away from a designated site. It is evident that SSSIs are much more numerous (4,853 nitrogen sensitive SSSIs vs 538 nitrogen sensitive SACs) and more widely dispersed than SACs, with the associated modelled mitigation zones being much larger for SSSIs, and more frequently overlapping.

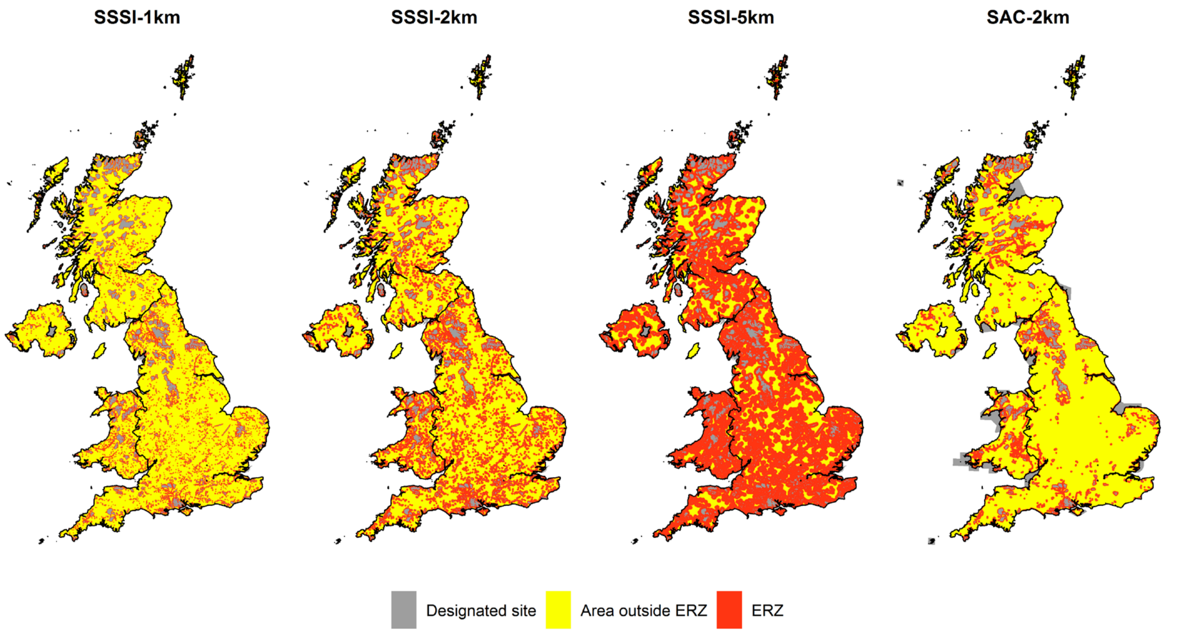


Figure 3-9. Emission Reduction Zones (ERZ) and Emission Displacement Zones (EDZ) used for the spatially targeted mitigation scenarios.

Atmospheric concentrations of NH_3 and NO_x

For the UK-wide and spatially targeted NH_3 mitigation scenarios, the results show that in relation to the 2030 NAPCP+DA baseline the key drivers for the spatial location and extent of concentration reductions are, as expected:

- the width/size of ERZ where mitigation is applied (vs. UK-wide application);
- the ambition of the mitigation scenarios;
- the geographical distribution of the designated sites; and
- the presence/absence of emission sources for applying mitigation measures.

[*N.B. All relevant maps, detailed descriptions and interpretation can be found in **Annex 4***]

For the UK-wide mitigation scenarios (2030 and 2040+ High Amb. exc./inc. cattle, respectively), the largest concentration decreases are mostly in the areas with the highest emission densities, and therefore the highest absolute emission reductions. In the spatially targeted scenarios, the results show that the concentration decreases are less widespread and limited to areas that have designated sites. One scenario standing out from the rest, with particularly different concentration patterns, is the EDZ scenario. For this scenario, results show atmospheric concentration increases in some areas of the country due to additional manure/slurry application that was displaced from 1 km zones around all N-sensitive SSSIs.

Regionally, the largest effects of more ambitious measures, whether modelled UK-wide or as spatially targeted scenarios, are found in Northern Ireland and the more intensive agricultural landscapes of England and SW Wales, with dairy, pig and poultry dominated areas most prominent in terms of concentration reductions. These patterns are not surprising, as they reflect the areas with highest emission densities and therefore highest mitigation potential. As expected, there are only minor NH_3 concentration decreases in the more remote parts of the UK, with relatively low agricultural activity, such as upland areas with only very extensive sheep and beef cattle farming at very low densities. Designated sites located in such areas are already relatively less affected by local emission sources, compared with sites in areas with much higher emission densities. The relatively localised effects of targeted emission mitigation on NH_3 concentrations is further illustrated in the local case studies presented in **Annex 5**, with key messages summarised in Section 3.2 of this report.

In relation to NO_x emissions the results show that scenarios that go beyond the ones modelled for 2030 BAU (WM) and 2030 NAPCP+DA conditions will result in further decrease in NO_x emission concentration across the UK and Devolved Administrations. The largest decreases are expected in areas with combustion activities, i.e. areas of the country which are the most densely populated and with the highest levels of traffic.

Atmospheric nitrogen deposition

The future mitigation scenarios that go beyond meeting the NECR targets, i.e. have more ambitious measures than the 2030 NAPCP+DA (NECR NO_x) baseline, achieve further decreases in N deposition. However, these decreases are less substantial than the large steps necessary to meet the NECR target (58 kt N, compared with 2017). The UK-wide 2030 High Amb. exc. cattle scenario achieves an additional decrease of 5.4 kt N, and the 2040+ High Amb. inc. cattle scenario a further 11.4 kt N (Table 3-6).

N deposition decreases are smaller for the spatially targeted scenarios than the UK-wide versions of the same scenarios, and overall N deposition decreases in line with increasing ERZ widths. The results for the EDZ scenario show no significant differences in total N deposition across the UK as a whole and it is comparable with the NAPCP+DA. This is because the EDZ scenario does not achieve any additional emission reductions for NO_x nor NH_3, compared with the NAPCP+DA (NECR-NOx) baseline. Instead, under the ERZ scenario emissions are removed from zones close to designated sites and placed further distant from the sensitive habitats.

The tree planting scenario (2040+ Trees SSSI 2km) shows a perhaps counter-intuitive decrease in N deposition, rather than the increase that would be expected, due to the presence of additional woodland planted and related increase in dry deposition. This is due to the way this scenario had to be implemented, as the 1 km x 1 km grid resolution model cannot represent the local processes of recapture in small optimised tree belts close to livestock houses and manure stores. These limitations meant that the recapture effect had to be implemented as a net emission reduction, thereby not capturing the actual emission from the local sources followed by the recapture within each affected model grid cell (as described in more detail in **Annex 2**).

Table 3-6. Summary of N deposition to the UK land area for all baseline and mitigation scenarios, split into the main components of wet, dry, reduced and oxidised nitrogen (kt N). The data represent grid square average N deposition, i.e. take into account the land cover within each model grid square to provide land cover dependent total deposition.

Scenario (all values kt N)	NHx-N dry	NHx-N wet	NOy-N dry	NOy-N wet	Total N
2017 Baseline	75.3	93.8	34.6	73.3	277.1
2030 Baseline BAU (WM)	76.1	86.5	22.8	54.1	239.5
2030 Baseline NAPCP+DA (NECR NOx)	67.2	79.7	20.9	51.4	219.1
2030 NAPCP+DA	67.2	79.6	20.5	51.0	218.4
2030 ERZ SAC 2km	66.8	79.3	20.5	51.0	217.6
2030 ERZ SSSI 1km	66.8	79.3	20.5	51.0	217.6
2030 ERZ SSSI 2km	66.3	79.0	20.5	50.9	216.8
2030 ERZ SSSI 5km	65.3	78.1	20.6	50.9	214.8
2030 High Amb. exc. cattle	64.6	77.6	20.6	50.9	213.7

2030 EDZ SSSI 1km	67.2	79.7	20.5	50.9	218.3
2040+ High Amb. inc. cattle	63.5	76.4	18.8	48.9	207.7
2040+ ERZ SSSI 2km inc cattle	66.0	78.4	18.8	49.0	212.1
2040+ Trees SSSI 2km	66.3	78.7	18.8	49.0	212.8

The partitioning of the different components of N deposition varies across the UK with more wet deposition in upland areas with higher precipitation. Wet deposition mostly originates from further afield and arrives through regional/long-distance atmospheric transport, principally in particulate form. By contrast, dry deposition, e.g. in the form of NO_2 and NH_3 gas, mostly originates more locally.

Further details including graphics and tables for the different UK countries are provided in **Annex 4**. In summary, it is notable that the reduced N fraction (NH_x), originating from NH_3 emissions, is much more prominent in Northern Ireland, where oxidised N (NO_y) is relatively less important than across other parts of the UK. In terms of wet deposition (implying more long-range transport), Scotland has much higher fractions than the other countries.
When analysing the results of the mitigation scenarios and assessing the effectiveness of UK-wide and spatially targeted measures for reducing N deposition, it is important to consider the differences between the main components of wet, dry, reduced and oxidised nitrogen.

3.1.3 Optimised spatially targeted scenarios description and rationale

Following the analysis of the initial 13 model runs for baseline and mitigation scenarios (Sections 3.1.1, 3.1.2) the most promising mitigation scenarios for 2030 were combined into two optimised spatially targeted scenarios, to maximise ecosystem benefits. The key measures that were combined included the ERZ and EDZ scenarios, with EDZ surrounding all SSSIs and ERZ of variable widths. The widths of the ERZ in the optimised scenarios were the minimum required to bring each site out of exceedance, if possible. The two scenarios were optimised for CLe and CL exceedance, respectively (CLe opt. ERZ (no urea), CL opt. ERZ (no urea)). For example, a site that did not exceed the 1 µg m^{-3} CLe was not assigned an ERZ, whereas a site that came out of CLe exceedance with a 1 km ERZ was assigned a 1 km ERZ in the CLe opt. ERZ (no urea) scenario, or else the 2 km width, *etc*. Sites that still exceeded the CLe with a 5 km ERZ were assigned a 5 km ERZ to reduce excess nitrogen additions as far as possible. The second optimised scenario assigned variable ERZ widths based on critical loads exceedance, in the same way as for CLe above. In addition to the ERZ and EDZ measures, the optimised scenarios were further enhanced with a UK-wide measure, replacing urea and UAN with low-emission fertiliser types, such as ammonium nitrate (Table 3-7).

In terms of overall UK emission reductions, both optimised emission scenarios were similar to each other, with the scenario optimised for reducing CLe exceedance estimated to decrease NH_3 emissions by 17.7 kt NH_3 (from NAPCP+DA - NECR NO_x) and the critical load optimised scenario providing a 17.5 kt NH_3 reduction. The addition of the urea/UAN replacement measure, provides the largest single emission reduction, ca 8.9 kt NH_3.

Table 3-7. Comparison of UK ammonia emission totals for optimised scenarios, by major sectors, with other relevant scenarios. Spatial targeting scenarios were modelled using Emission Reduction Zones (ERZ) and Emission Displacement Zones (EDZ). “HGD” refers to horses on agricultural holdings, goats and farmed deer (minor livestock categories). “Other” refers to non-agricultural emission sources, which includes the waste, transport, nature, industrial, *etc*. sectors. CLe refers to critical levels and CL to critical loads. Units: kt NH_3

Scenario	Cattle	Mineral fertiliser	HGD/ minor	Pigs	Poultry	Sheep	Other	Total
2017 Baseline	115.8	44.9	1.4	18.6	37.7	9.6	61.4	289.3
2030 NAPCP+DA (NECR NO_x)	94.9	28.7	1.4	17.1	34.6	9.0	67.9	253.6
2030 ERZ SSSI 1km	94.0	28.7	1.4	16.7	34.0	9.0	67.9	251.7
2030 ERZ SSSI 2km	93.0	28.7	1.4	16.3	33.3	9.0	67.9	249.6
2030 ERZ SSSI 5km	90.9	28.7	1.4	15.3	31.4	9.0	67.9	244.6
2030 High Amb. exc. cattle	89.8	28.7	1.4	14.7	30.3	9.0	67.9	241.8
2030 EDZ SSSI 1km	94.9	28.7	1.4	17.1	34.6	9.0	67.9	253.6
2030 CLe opt. ERZ SSSI (no urea)	91.0	19.8	1.4	15.4	31.4	9.0	67.9	235.9
2030 CL opt. ERZ SSSI (no urea)	91.0	19.8	1.4	15.4	31.5	9.0	67.9	236.0

Ammonia concentrations and N deposition patterns under the two optimised scenarios are relatively similar, with both scenarios including the same UK-wide EDZ and urea/UAN replacement measures and many of the ERZ being similar widths. Compared with the 2017 baseline, large agriculturally dominated lowland areas of England and most of Northern Ireland are expected to see decreases in NH_3 concentrations of up to 1 µg NH_3, (at a 1 km grid resolution) under the optimised scenarios. Substantial improvement is also estimated compared with the 2030 NAPCP+DA (NECR NO_x) baseline. There are similar trends for N deposition to low-growing semi-natural vegetation, estimated to receive up to 5 kg N ha^{-1} yr^{-1} less N deposition in the optimised scenarios than under the 2017 baseline scenario. For woodland vegetation, even higher reductions in N deposition are estimated.

3.1.4 Ammonia critical level exceedance

In terms of assessing the effect of NH_3 concentrations at sites, three key metrics were primarily used to compare exceedance under each mitigation scenario. Full details of these metrics can be found in Section 2.2 of this report. In summary:

- Designation Weighted Indicator (DWI): provides an indication of the number of sites where NH_3 concentrations exceed the critical level at any point of the site;
- Area Weighted Indicator 1 (AWI-1) provides an indication of 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; and
- Area Weighted Indicator 2 (AWI-2) provides an indication of actual exceeded areas within protected sites, i.e. the percentage area of sites that are predicted to be below the CLe/CL. This indicator therefore enables tracking of areas gradually expected to come out of exceedance with increasing mitigation efforts in the scenarios tested – whereas the DWI and AWI-1 for a site only change once the whole site is estimated to no longer exceed. When summarising AWI-2 across the UK and countries, the exceeded area is therefore always smaller than under AWI-1.

These indicators are presented in Table 3-8 for the 1 µg m^{-3} critical level (CLe), set for the most sensitive species. Under the 2017 baseline scenario, the model results estimate the majority of SSSIs in England and Northern Ireland are estimated to exceed this threshold for the more precautionary indicators (DWI, AWI-1), at >89%. For Wales, fewer sites exceed the

1 µg m^{-3} critical level with approximately 66% of sites in exceedance for the DWI indicator and 71% for AWI-1. N-sensitive SSSIs situated in Scotland benefit from being in relatively remote and cleaner areas, away from substantial NH_3 emission sources. Only 23% of sites were found to be in exceedance for the DWI, i.e. number of sites, and 10% for the AWI-1 indicator. The AWI-2 indicator which refers to the overall area exceeded within sites, i.e. counts specific exceeded areas within sites only, is substantially lower for much of the UK, except for Northern Ireland where >80% of SSSI area exceeds the 1 µg m^{-3} CLe.

The model results indicate that the measures implemented under the 2030 NAPCP+DA baseline scenario are more effective across Wales, Scotland and Northern Ireland than for England, in terms of the number of sites coming out of CLe exceedance (DWI), with decreases in exceedance of around 3-5%. Under the 2030 BAU (WM) baseline scenario exceedances of the 1 µg m^{-3} CLe are expected to increase for most indicators across England, Wales and Scotland. This is due to very few NH_3 measures included in this scenario and some emission sectors increasing due to future activity projections (see Section 3.1.1 for details).

Ammonia concentrations for the two optimised scenarios are relatively similar for two reasons. Firstly, the EDZ and urea/UAN replacement measures implemented across both optimised scenarios were identical. Secondly, many of the ERZ required similar widths for achieving either non-exceedance of the 1 µg CLe or the relevant CL, or to at least decrease concentrations and deposition as much as possible, while still in exceedance. The optimised scenarios provide a substantial decrease in the number of sites in exceedance, compared with the 2030 NAPCP+DA (NECR NO_x) baseline scenario. This ranges from an additional 4.1 % of sites coming out of exceedance in Northern Ireland to 6.5 % in Wales.

In terms of additional areas within sites coming out of exceedance (i.e. AWI-2), this is more substantial in England (~8.1 %) and Northern Ireland (~7.9 %) than in Scotland (0.6 %), where only 1.7 % of the areas within Scottish N-sensitive SSSIs were exceeded under the 2030 NAPCP+DA (NECR NO_x) baseline scenario.

Table 3-8. UK-wide and spatially target mitigation scenarios: percentage of ammonia critical level exceedance (>1 µg m^{-3}) in nitrogen sensitive SSSIs by UK country (England, Wales, Scotland, Northern Ireland). Indicators shown are the DWI (Designation Weighted Indicator) and AWI (Area Weighted Indicators).

	England			Wales			Scotland			Northern Ireland		
Scenario	DWI	AWI-1	AWI-2	DWI	AWI-1	AWI-2	DWI	AWI-1	AWI-2	DWI	AWI-1	AWI-2
2017 Baseline	89.9	90.5	42.3	65.7	70.8	13.9	23.2	10.2	2.4	90.4	97.1	84.3
2030 BAU (WM)	92.5	93.2	49.6	69.3	69.8	15.4	26.0	11.0	2.6	87.9	95.4	83.1
2030 NAPCP+DA (NECR NOx)	88.4	88.5	37.7	62.4	66.5	10.8	20.5	9.8	1.7	85.4	94.1	77.2
2030 ERZ SAC 2km	88.1	88.4	36.9	61.7	66.4	10.3	20.2	9.8	1.6	85.4	94.1	76.4
2030 ERZ SSSI 1km	88.0	88.4	36.9	61.7	66.4	10.5	20.1	9.8	1.6	85.4	94.1	76.7
2030 ERZ SSSI 2km	87.8	88.3	36.4	61.5	66.3	10.2	19.7	9.6	1.5	85.0	94.1	76.2
2030 ERZ SSSI 5km	87.5	88.3	35.2	60.7	55.9	9.7	18.9	9.5	1.4	85.0	94.1	74.0
2030 High Amb. exc. cattle	87.2	88.0	34.6	60.5	55.9	9.5	18.8	9.5	1.4	84.2	94.0	69.8
2030 EDZ SSSI 1km	87.1	85.4	35.9	58.9	53.6	9.6	18.3	9.3	1.3	82.1	91.5	76.1

2040+ ERZ SSSI 2km inc. cattle	87.6	88.3	36.1	61.1	56.0	9.8	19.4	9.6	1.5	85.0	94.1	75.9
2040+ High Amb. inc. cattle	86.7	87.5	33.4	59.8	55.9	8.9	18.4	9.4	1.3	82.5	94.0	64.6
2040+ Trees SSSI 2km	87.7	88.3	36.5	61.2	66.3	10.1	19.0	9.5	1.5	85.4	94.1	76.4
2030 CLe opt. ERZ SSSI	83.1	80.7	29.5	55.9	53.0	7.7	14.9	9.2	1.1	81.3	91.5	69.3
2030 CL opt. ERZ SSSI	83.1	80.7	29.6	55.9	53.0	7.7	15.2	9.2	1.1	81.3	91.5	69.3

For the 3 $\mu g\ m^{-3}$ critical level (Table 3-9), exceedances are largest for Northern Ireland, with 23% of N-sensitive SSSIs exceeded under 2017 baseline, followed by England 9%, Wales 4 % and Scotland 1%. Substantial improvements are expected for the 2030 NAPCP+DA (NECR-NOx) baseline scenario, with the largest decreases in Northern Ireland and England with 7 % and 3 % fewer sites in exceedance, respectively (DWI). The higher ambition UK-wide mitigation scenarios are estimated to bring additional sites out of exceedance, with the spatially targeted ERZ scenarios providing increasing benefits with increasing widths of the mitigation zones.

The proportion of sites in exceedance of the 3 $\mu g\ m^{-3}$ CLe under the optimised mitigation scenarios decreases by approximately 50% under 2030 NAPCP+DA (NECR NO_x) for England and Northern Ireland and by a third for Wales. For all countries, the area within sites (i.e. AWI-2) above the 3 $\mu g\ m^{-3}$ threshold is relatively small under all emission scenarios.

Table 3-9. UK-wide and spatially target mitigation scenarios: Percentage of ammonia critical level exceedance (> 3 $\mu g\ m^{-3}$) in nitrogen sensitive SSSIs by UK country (England, Wales, Scotland, Northern Ireland). Indicators shown are the DWI (Designation Weighted Indicator) and AWI (Area Weighted Indicators).

	England			Wales			Scotland			Northern Ireland		
Scenario	DWI	AWI-1	AWI-2	DWI	AWI-1	AWI-2	DWI	AWI-1	AWI-2	DWI	AWI-1	AWI-2
2017 Baseline	9.3	20.9	1.0	3.6	4.8	0.4	1.0	2.6	0.0	22.9	48.0	1.3
2030 BAU (WM)	10.5	19.5	1.1	4.0	4.8	0.5	0.9	2.6	0.0	20.0	43.3	1.2
2030 NAPCP+DA (NECR NOx)	5.8	14.9	0.6	1.9	4.2	0.3	0.8	2.6	0.0	15.8	41.8	0.9
2030 ERZ SAC 2km	5.6	14.7	0.6	1.8	3.9	0.3	0.8	2.6	0.0	15.4	41.8	0.9
2030 ERZ SSSI 1km	5.4	14.7	0.6	1.8	3.9	0.3	0.8	2.6	0.0	15.4	41.8	0.8
2030 ERZ SSSI 2km	5.1	14.7	0.5	1.8	3.9	0.3	0.6	2.6	0.0	14.6	41.7	0.8
2030 ERZ SSSI 5km	4.9	14.7	0.5	1.6	3.9	0.2	0.6	2.6	0.0	14.2	41.6	0.8
2030 High Amb. exc. cattle	4.9	14.7	0.5	1.6	3.9	0.2	0.6	2.6	0.0	13.3	41.6	0.8
2030 EDZ SSSI 1km	3.9	12.9	0.3	1.0	3.7	0.1	0.6	2.6	0.0	12.1	41.3	0.7
2040+ ERZ SSSI 2km inc. cattle	5.0	14.7	0.5	1.6	3.9	0.2	0.6	2.6	0.0	14.6	41.7	0.8
2040+ High Amb. inc. cattle	4.6	14.6	0.5	1.4	3.8	0.2	0.6	2.6	0.0	12.5	41.5	0.7
2040+ Trees SSSI 2km	5.4	14.7	0.6	1.9	4.2	0.3	0.6	2.6	0.0	15.4	41.8	0.8
2030 CLe opt. ERZ SSSI	2.6	12.2	0.2	0.5	3.1	0.1	0.6	2.6	0.0	8.8	41.1	0.7

2030 CL opt. ERZ SSSI	2.6	12.2	0.2	0.5	3.1	0.1	0.6	2.6	0.0	8.8	41.1	0.7

Table 3-10 presents the number of sites coming out of exceedance, compared with the 2017 baseline. Overall, atmospheric NH_3 concentrations across 138 UK SSSIs currently exceeding 1 µg m^{-3} CLe are expected to drop below this threshold with the implementation of the 2030 NAPCP+DA (NECR NOx) measures.

Approximately 46% of these SSSIs are in England, 22% in Wales, 20% in Scotland and 11% in Northern Ireland. For the optimisation tailored with ERZ widths chosen to minimise critical level exceedance, 419 SSSIs across the UK no longer exceed the1 µg m^{-3} threshold (n = 417 for 2030 CL opt. ERZ SSSI), compared with the 2017 baseline.

Table 3-10. Additional number of nitrogen sensitive UK SSSIs overall (compared with the 2017 baseline) that are no longer in exceedance of the 1 µg m^{-3} critical level under each of the emission mitigation scenarios. The 1 µg m^{-3} critical level is relevant for assessing lichens, mosses and bryophytes. Exceedance of critical levels has been assessed based on the maximum estimated concentrations at sites.

Scenario	England	Wales	Scotland	NI	UK
2030 BAU (WM)	0	5	6	8	19
2030 NAPCP+DA (NECR NOx)	64	31	28	15	138
2030 ERZ SAC 2km	73	36	32	15	156
2030 ERZ SSSI 1km	74	36	33	15	158
2030 ERZ SSSI 2km	81	37	38	16	172
2030 ERZ SSSI 5km	86	43	46	16	191
2030 High Amb. exc. cattle	93	44	47	19	203
2030 EDZ SSSI 1km	98	59	51	24	232
2040+ ERZ SSSI 2km inc. cattle	82	39	42	16	179
2040+ High Amb. inc. cattle	107	50	50	23	230
2040+ Trees SSSI 2km	81	39	45	15	180
2030 CLe opt. ERZ SSSI with EDZ (no urea)	223	84	86	26	419
2030 CL opt. ERZ SSSI with EDZ (no urea)	223	84	84	26	417

The implementation of the 2030 NAPCP+DA (NECR NOx) measures is estimated to bring 157 of the 368 UK SSSIs that are currently exceeding the 3 µg m^{-3} CLe threshold out of exceedance (Table 3-11). The majority (76%) of these SSSIs are in England, with 14% in Northern Ireland, 9% in Wales, and 2% in Scotland.

The higher ambition UK-wide mitigation scenarios are estimated to bring a further 40 and 51 SSSIs, respectively, out of exceedance. It is notable that the 5 km ERZ is almost as successful as the same scenario implemented UK-wide. In terms of the non-optimised scenarios, the EDZ scenario brings the most sites out of exceedance with 21 more sites than the 2040+ UK-wide highest ambition scenario which includes regulation of large cattle farms. The optimised scenarios are estimated to bring 280 SSSIs across the UK out of exceedance for the 3 µg m^{-3} CLe compared with the 2017 baseline. When compared with the 2030 NAPCP+DA (NECR NO_x) baseline, the optimised scenarios bring 123 additional sites out of exceedance.

Table 3-11. Additional number of nitrogen sensitive UK SSSIs (compared with the 2017 baseline) that are no longer in exceedance of the 3 µg m^{-3} critical level under each of the emission scenarios. The 3 µg m^{-3} critical level is relevant for assessing higher plants. Exceedance of critical levels has been assessed based on the maximum estimated concentrations at sites.

Scenario	England	Wales	Scotland	Northern Ireland	UK
2030 BAU (WM)	23	1	2	12	38
2030 NAPCP+DA (NECR NOx)	119	14	3	22	157
2030 ERZ SAC 2km	127	16	3	23	168
2030 ERZ SSSI 1km	133	16	3	23	174
2030 ERZ SSSI 2km	142	16	4	25	186
2030 ERZ SSSI 5km	149	17	4	26	195
2030 High Amb. exc. cattle	149	17	4	28	197
2030 EDZ SSSI 1km	175	22	4	32	229
2040+ ERZ SSSI 2km inc. cattle	144	17	4	25	189
2040+ High Amb. inc. cattle	158	20	4	30	208
2040+ Trees SSSI 2km	132	14	4	23	172
2030 CLe opt. ERZ SSSI with EDZ (no urea)	215	25	4	41	280
2030 CL opt. ERZ SSSI with EDZ (no urea)	215	25	4	41	280

Figure 3-10 shows the average area-weighted exceedance above the 1 µg NH_3 CLe at N-sensitive SSSIs under each mitigation scenario. This quantification of the average area weighted concentration above the CLe, shows the wider benefits of increasingly ambitious mitigation across designated sites. While the number of sites achieving non-exceedance increases with ambition levels, those that remain in exceedance also benefit from decreased concentrations. For a large proportion of sites in Scotland and Wales the area-weighted concentration is estimated to be only marginally above the 1 µg CLe, by up to 0.2 µg NH_3 m^{-3} (yellow bars in Figure 3-10).

The average area-weighted exceedance above the 3 µg NH_3 CLe at N-sensitive SSSIs under each mitigation scenario are presented in Figure 3-11. The proportion of sites in exceedance of the 3 µg NH_3 CLe are much lower than for the 1 µg CLe. This is especially the case in Scotland where only 7 sites (with areas in Scotland) are in exceedance of the 3 µg CLe under NAPCP+DA (NECR NO_x). While the number of sites achieving non-exceedance increases with ambition levels, those that remain in exceedance also benefit from decreased concentrations. In the same way as for the 3 µg NH_3 CLe, sites that are coming out of exceedance with mitigation efforts are those with the lowest levels of excess NH_3 concentrations.

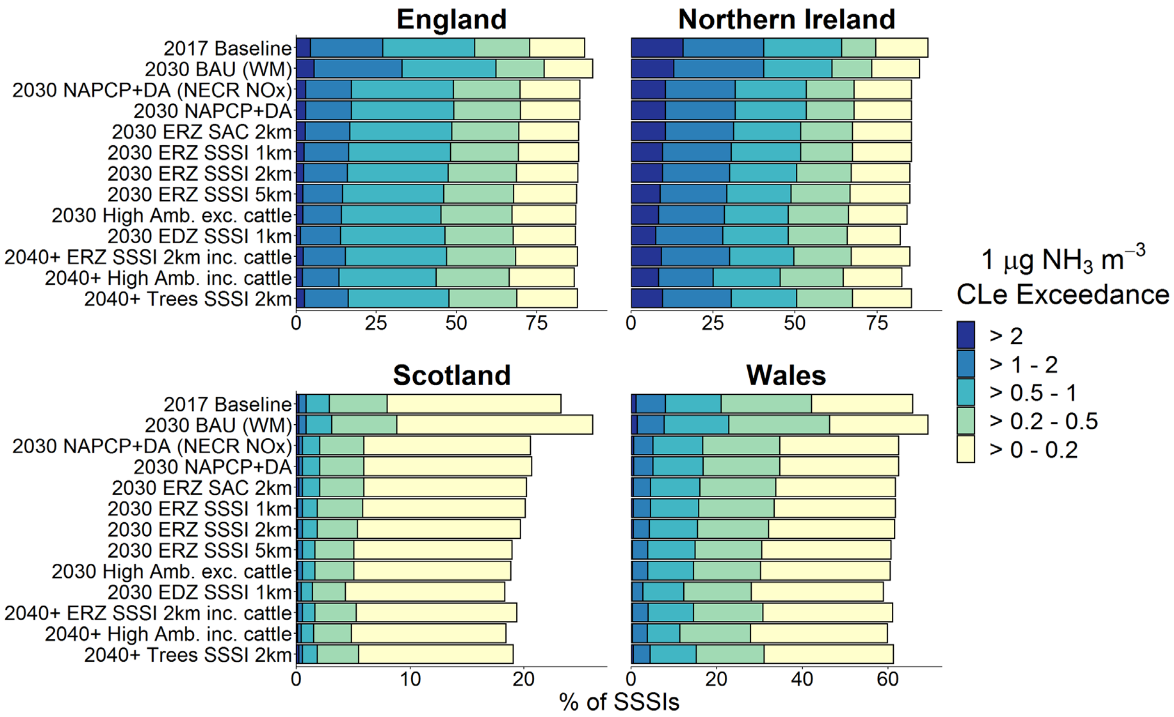


Figure 3-10. Average-area weighted exceedance above the 1 ug critical level at UK nitrogen sensitive SSSI sites (in exceedance of critical level).

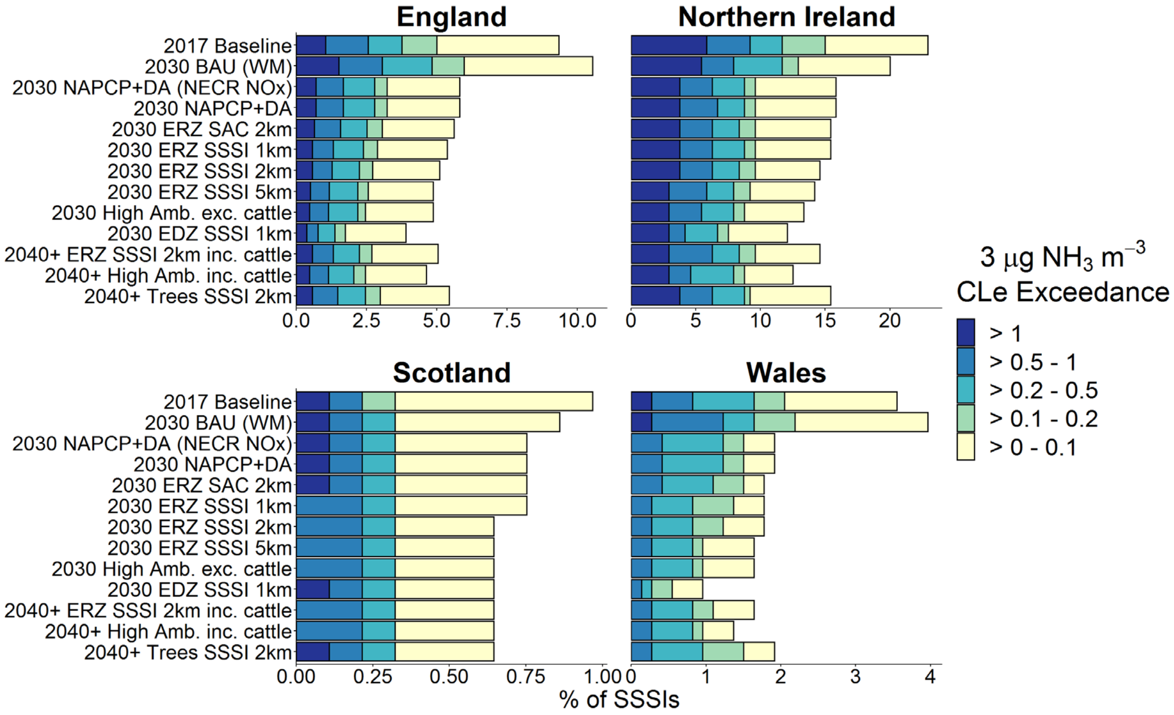
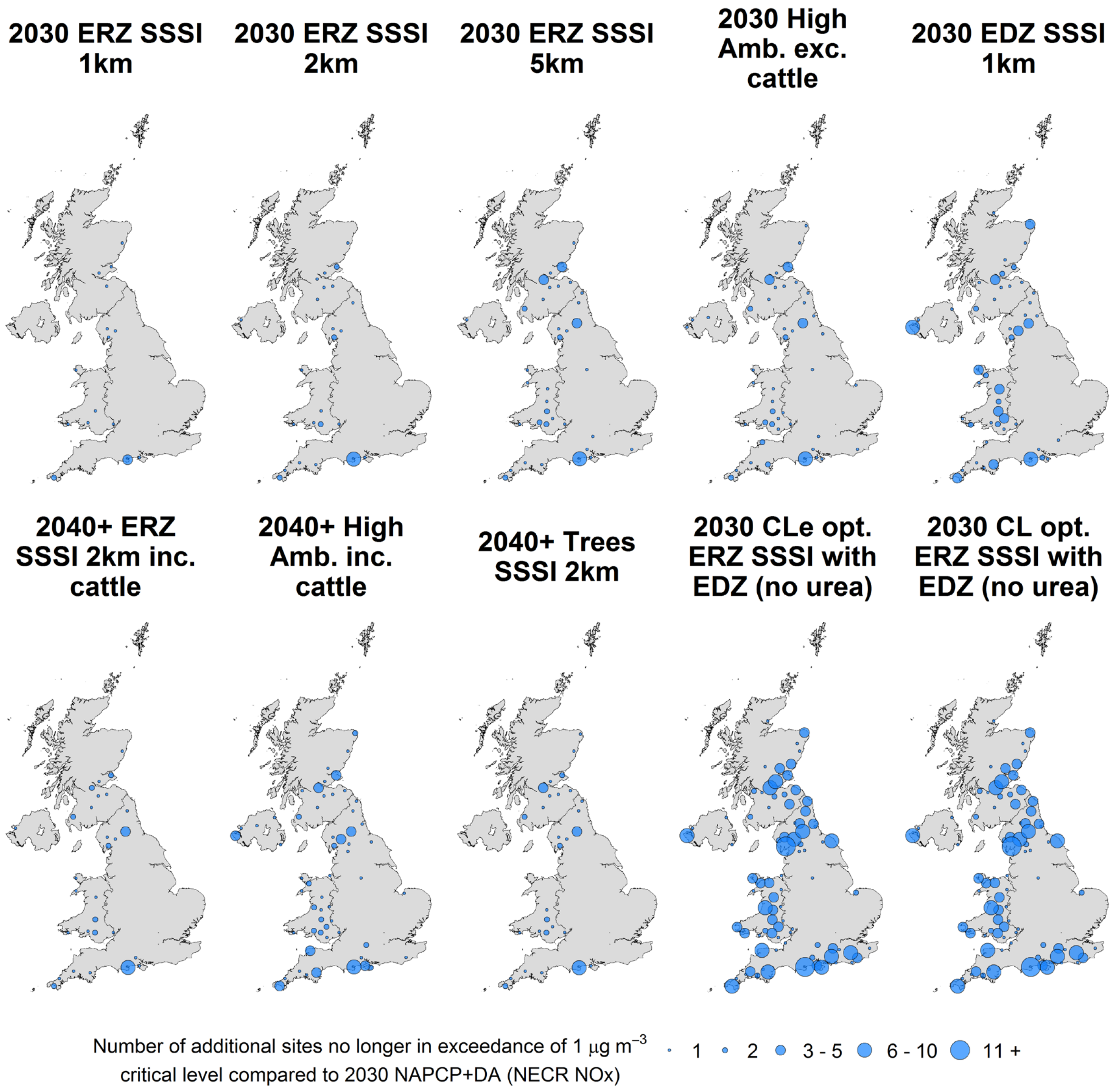


Figure 3-11. Average-area weighted exceedance above the 3 ug critical level at UK nitrogen sensitive SSSI sites (in exceedance of critical level).

The spatial distribution of additional sites brought out of exceedance compared with NAPCP+DA (NECR NO_x) for the 1 and 3 µg m^{-3} critical levels is shown in Figures 3-12 and 3-13, respectively. Figure 3-12 shows that areas of the UK with sites that are currently in exceedance benefit most from the optimised scenarios are Scotland, Wales and NW England as well as the south coast of England and the west of Northern Ireland.

The three types of measures combined in the optimised scenarios, i.e. higher ambition ERZ, EDZ and urea/UAN replacement, achieve the additional environmental benefits, with more sites no longer exceeding critical levels. Compared with the 2017 baseline, approximately 280 additional SSSIs no longer exceed the 1 µg m^{-3} CLe.



2030 ERZ SSSI 1km

2030 ERZ SSSI 2km

2030 ERZ SSSI 5km

2030 High Amb. exc. cattle

2030 EDZ SSSI 1km

2040+ ERZ SSSI 2km inc. cattle

2040+ High Amb. inc. cattle

2040+ Trees SSSI 2km

2030 CLe opt. ERZ SSSI with EDZ (no urea)

2030 CL opt. ERZ SSSI with EDZ (no urea)

Figure 3-12. Maps showing the additional number of nitrogen sensitive UK SSSIs (compared with the NAPCP+DA NECR NO_x scenario) that are no longer in exceedance of the 1 µg m^{-3} critical level under each of the emission scenarios (relevant to SSSIs). The 1 µg m^{-3} critical level is relevant for assessing lichens, mosses and bryophytes. Exceedance of critical levels has been assessed based on the maximum estimated concentrations at sites. Sites clustered together with nearby site up to a distance of 50 km for visualisation.

In terms of sites being brought under the 3 µg m^{-3} critical level, the main areas to benefit span the lowland areas with higher emission densities in England and Northern Ireland, where the majority of sites exceeding the 3 µg m^{-3} CLe are located (Figure 3-13).

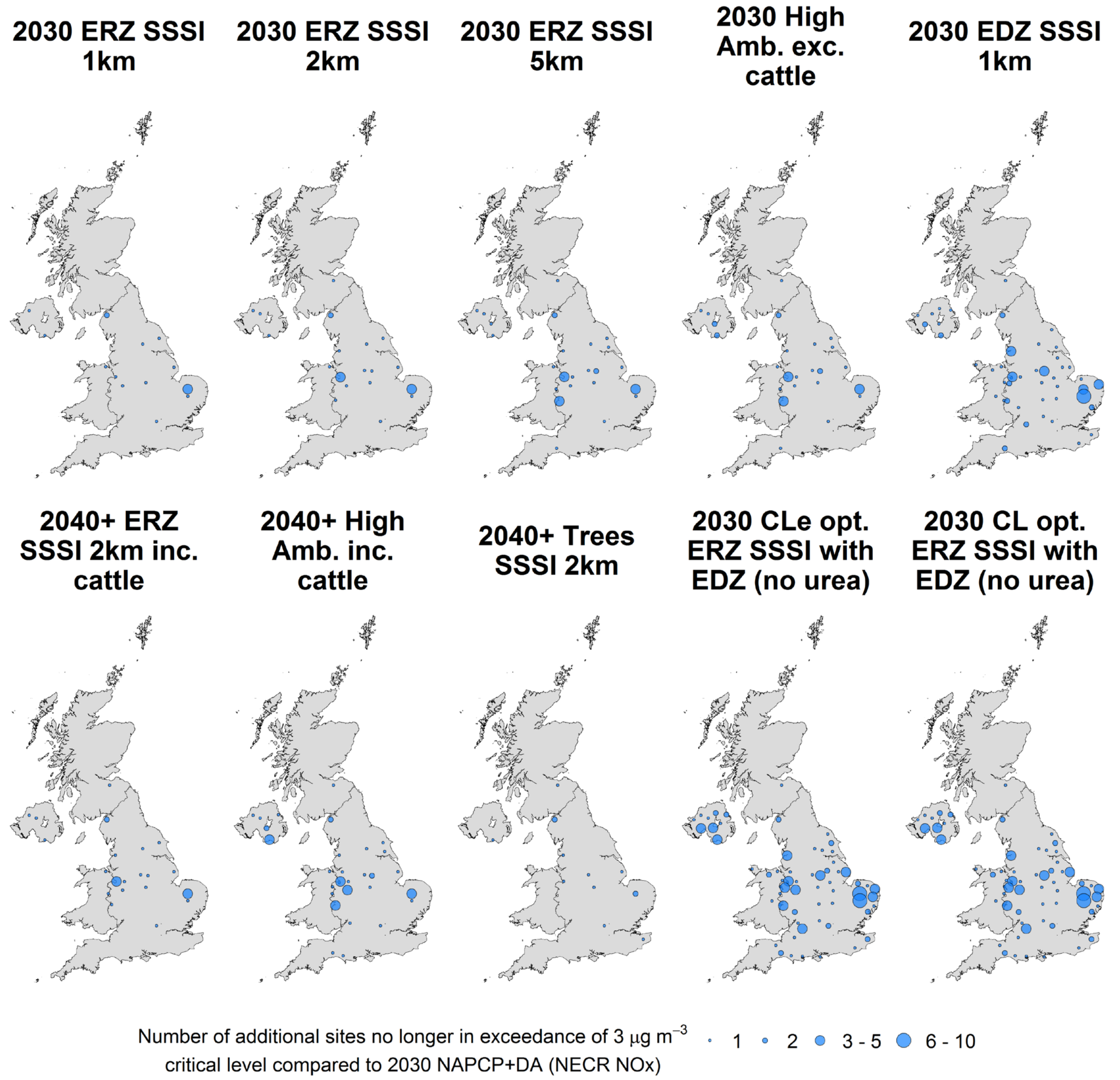


Figure 3-13. Maps showing the additional number of nitrogen sensitive UK SSSI sites (compared with the NAPCP+DA NECR NO_x scenario) that are no longer in exceedance of the 3 μg m^{-3} critical level under each of the emission scenarios (relevant to SSSIs). The 3 μg m^{-3} critical level is relevant for assessing higher plants. Exceedance of critical levels has been assessed based on the maximum estimated concentrations at sites. Sites clustered together with nearby site up to a distance of 50 km for visualisation.

3.1.5 Nutrient nitrogen critical loads exceedance

The proportion of N-sensitive SSSIs that exceed critical loads under all scenarios decreases with increasing ambition of mitigation measures. The largest change in exceedance is due to the substantial reductions in emissions and subsequently deposition expected in meeting the NECR targets. Further reductions in sites exceeding their critical loads are estimated in line with levels of ambition in further emission reductions. In terms of excess nitrogen, the results are similar with the largest step change being the measures needed to meet the 2030 NECR targets. Overall, the amount of excess N deposition (AAE) is largest in Northern Ireland and England, across all scenarios, and smallest in Scotland, much smaller than across the rest of the UK (Figure 3-14).

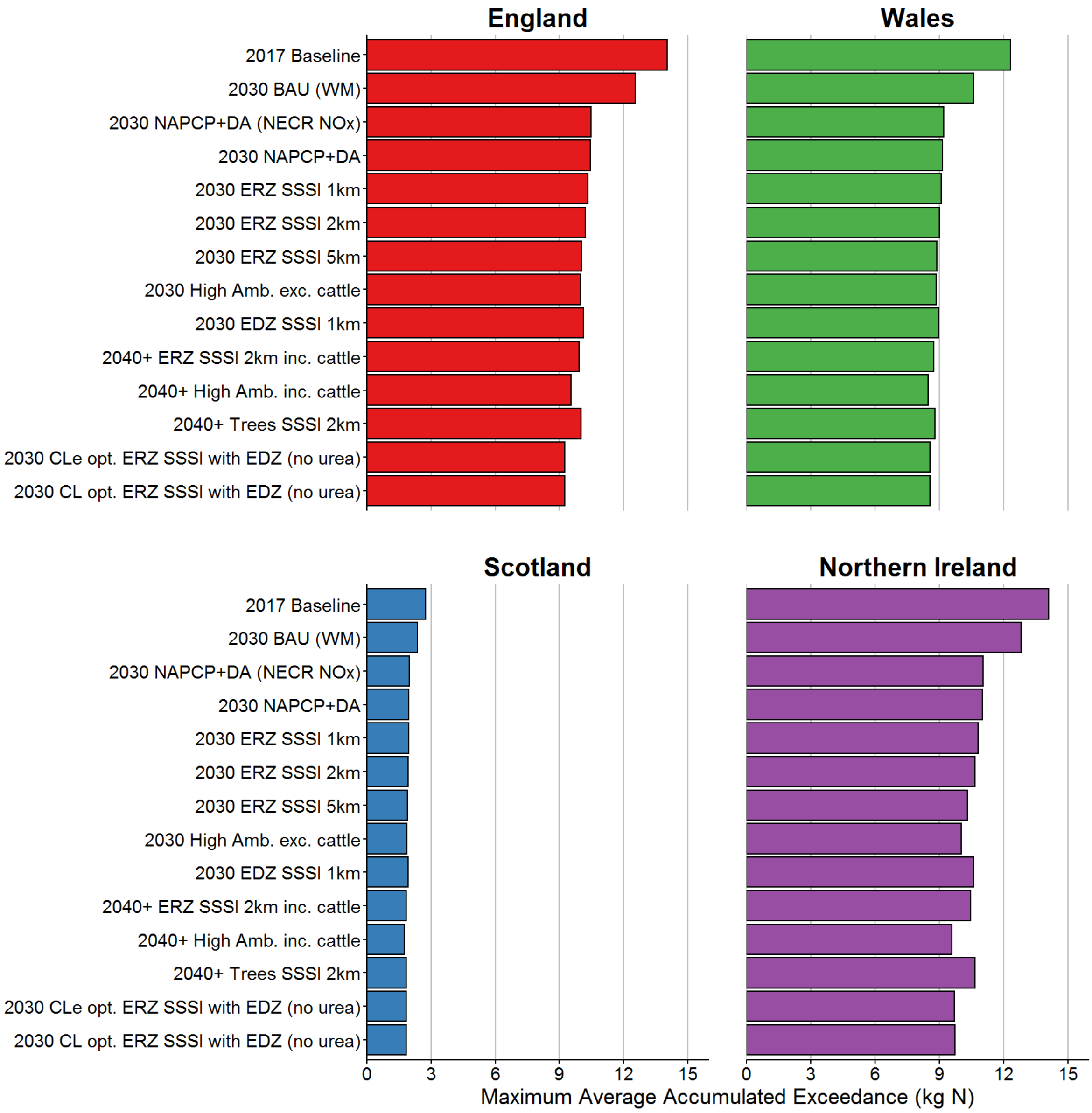


Fig. 3-14. A comparison of excess nitrogen (maximum average accumulated exceedance, kg N) for nitrogen-sensitive UK SSSIs with critical loads information (n = 4,727) under each emission scenario. Recently designated sites where critical load information is not available are not included in this plot. The database of sensitive features used by the NFC was collated in ~2011 and therefore does not have information about all sites.

Figure 3-15 presents the spatial distribution of the additional sites that are estimated to be no longer in exceedance of their critical loads, compared with the NAPCP+DA (NECR NO_x). These sites are located across the UK, in areas of higher and lower emission density, showing that the impact of emission reductions can have wide ranging effects due to medium and long-range transport and wet deposition as well as more localised dry deposition reductions.

The spatial distribution of the sites estimated to no longer exceed their CL under the optimised scenarios focuses on central, southern and eastern England, eastern Scotland and coastal areas of Wales and SW England, with the Northern Irish sites being located south of Lough Neagh and near the southern border (for additional data and tables for critical loads exceedance see Section 6 in **Annex 4**).

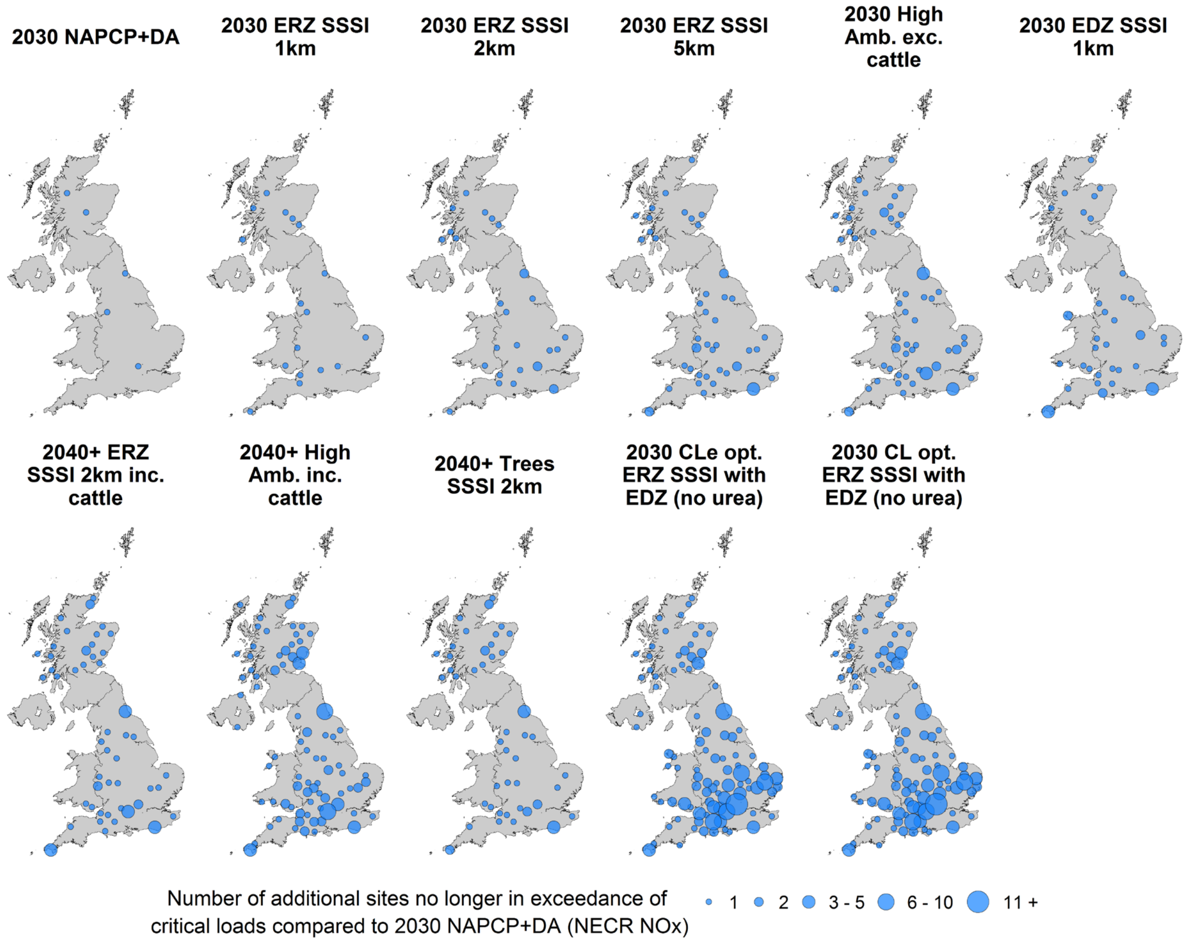


Figure 3-15. Maps showing the additional number of nitrogen sensitive UK SSSIs (compared with the NAPCP+DA NECR NO_x scenario) that are no longer in exceedance of critical loads under each mitigation scenarios relevant to SSSIs. This figure excludes the 127 SSSIs where critical load information is unknown. Sites clustered together with nearby site up to a distance of 50 km for visualisation.

3.2 Clean Air Strategy target: deposition to protected sensitive habitats

For all scenarios, a metric was calculated that can be related to the UK Government's Clean Air Strategy (CAS) target for 2030, i.e. a quantification of *total reactive N deposition onto protected priority sensitive habitats*. The definition of "protected priority sensitive habitats" remains under discussion by JNCC and Defra, so this study has used the set of priority habitats that are currently reported in the annual Trends Report (Rowe *et al*. 2020; see **Annex 4**, Section 4.2). Deposition of reactive N onto these habitats follows a similar geographical pattern to overall deposition. Mean N deposition onto N-sensitive priority habitats is similar for England, Wales and Northern Ireland and lower for Scotland.

The CAS target for England is expressed as a 17 % decrease in N deposition onto N-sensitive priority habitats by 2030, so the scenarios are most easily compared by looking at percentage decrease in this statistic. Percentage decreases since 2017 (the Nitrogen Futures baseline) are shown in **Annex 4**, Table 4-4. However, a 2016 baseline is used to assess progress towards the CAS target, as explained in the Trends Report 2020 (Rowe *et al*. 2020). This means that percentage decreases will be larger than shown in that table (**Annex 4**, Table 4-4). In Table 3-12, percentage decreases have been expressed from a 2016 baseline, by allowing for the observed decrease between 2016 and 2017 (3.0% in England, 1.7% in Wales, 1.2% in Scotland, 3.5% in Northern Ireland and 1.7% for all UK; Rowe *et al*. 2020). For example, the 2030 *NAPCP+DA (NECR NOx)* baseline scenario was projected to decrease N deposition onto N-sensitive priority habitats in England by 16.5 % over the period 2017-2030. Allowing for the observed decrease between 2016 and 2017, this corresponds to a decrease of 18.9 % between 2016 and 2030.

The estimated decrease from a 2016 baseline was more than 17% for all countries of the UK under *2030 NAPCP+DA (NECR NOx)* and all more stringent scenarios. The BAU (WM) scenario was not projected to meet the target, however, with only an estimated 9.7 % decrease 2016-2030. The most effective optimised mitigation scenario, *CLe opt. ERZ SSSI with EDZ (no urea)*, resulted in an estimated 23.3 % decrease in N deposition onto N-sensitive priority habitats in England 2016-2030.

Updates to the maps delineating protected priority sensitive habitats for the UK countries are expected, so numbers presented here should be considered preliminary. Relative changes in N deposition to any set of habitats are expected to be similar, so the projected percentage decreases (Table 3-12) are likely to be representative of results obtained using the final definition. However, if “protected priority sensitive habitats” are defined as areas within designated sites and/or give greater weight to areas within designated sites, the effects will be larger for the scenarios that include spatial targeting measures.

Table 3-12. Percentage change in mean deposition of total reactive N onto nutrient-N sensitive priority habitat in kg ha^{-1} year^{-1} from 2016 baseline, by country. Estimated from observed change 2016-2017 and simulated changes after 2017 under the different scenarios.

	Percentage change in area-weighted mean deposition of total reactive N onto nutrient-N sensitive priority habitat, by country				
Scenario	**England**	**Wales**	**Scotland**	**Northern Ireland**	**UK**
2030 BAU (WM)	-9.7	-11.2	-12.6	-9.7	-10.9
2030 NAPCP+DA (NECR NOx)	-18.9	-18.4	-18.4	-17.8	-18.2
2030 NAPCP+DA	-19.0	-18.7	-18.6	-17.9	-18.4
2030 ERZ SAC 2km	-19.4	-19.1	-18.8	-18.6	-18.7
2030 ERZ SSSI 1km	-19.4	-19.0	-18.8	-18.4	-18.7
2030 ERZ SSSI 2km	-19.8	-19.4	-19.0	-19.0	-19.1
2030 ERZ SSSI 5km	-20.7	-20.1	-19.6	-20.8	-19.9
2030 High Amb. exc. cattle	-21.1	-20.4	-20.0	-22.4	-20.3
2030 EDZ SSSI 1km	-19.4	-18.8	-18.6	-17.9	-18.5
2040+ ERZ SSSI 2km inc. cattle	-21.1	-20.8	-20.5	-19.8	-20.4
2040+ High Amb. inc. cattle	-22.9	-22.3	-22.0	-24.2	-22.2
2040+ Trees SSSI 2km	-20.8	-20.6	-20.4	-19.1	-20.2
2030 CLe opt. ERZ SSSI (no urea)	-23.3	-21.0	-20.2	-21.7	-21.2
2030 CL opt. ERZ SSSI (no urea)	-23.2	-21.0	-20.2	-21.7	-21.2

Vegetation-specific N deposition maps at a 1 x 1 km grid resolution can be found in **Annex 4** for all scenarios, separately for low-growing semi-natural vegetation and woodland.

3.3 Local scale assessment

The effectiveness of the mitigation scenarios at the local scale was assessed by analysing 15 detailed SSSI case studies (Figure 3-16) representative of different types and levels of atmospheric N pressures. The individual case studies are available in **Annex 5** to this report. The case studies summarise site characteristics, N sensitivity, all model outputs at the 1 km grid scale and more detailed information where available.

The local assessments aimed to answer the following key questions across the wide range of different types of sites and levels of atmospheric N pressures:

1. Can the UK-scale modelling outputs identify and represent local atmospheric N pressures at the local scale for each of the sites analysed?
2. Would spatial targeting of measures be a suitable strategy to decrease atmospheric N input locally?

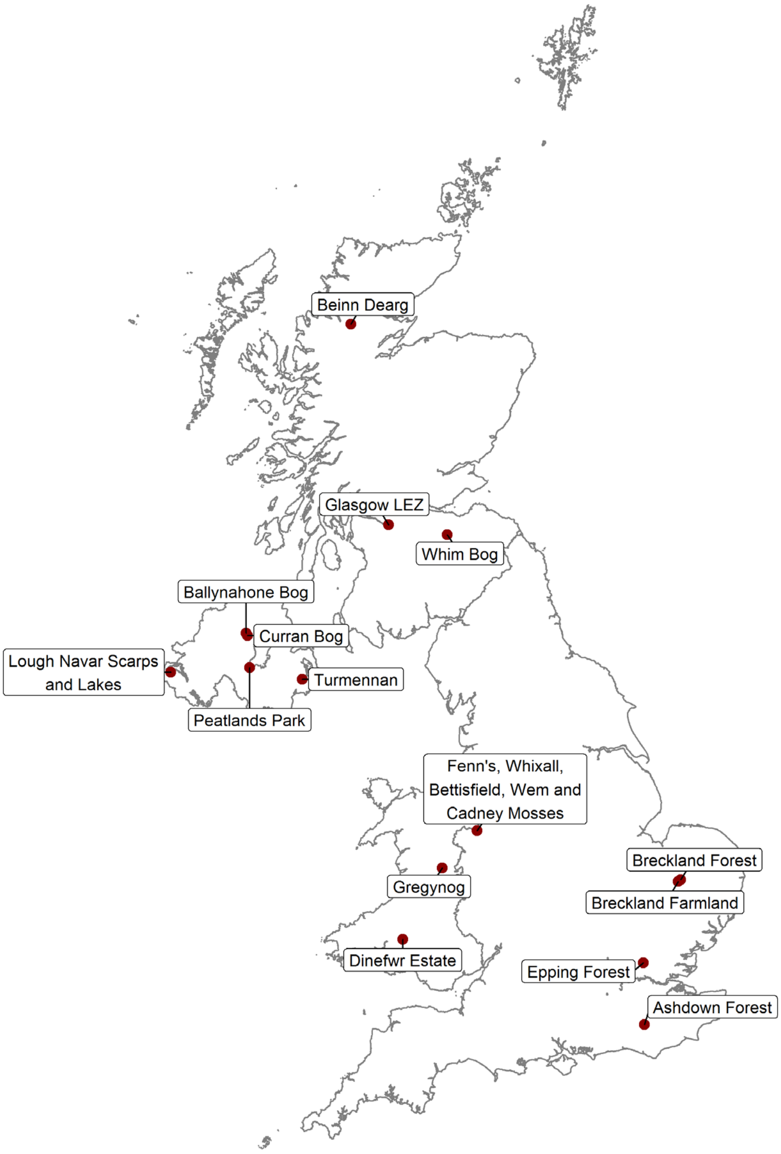


Figure 3-16. Location of case study sites selected for the local scale assessment.

3.3.1 Local scenario results for case studies

The site profiles were grouped into the following top-level summary categories (Table 3-13):

- Sites with N-sensitive semi-natural habitats and designated features; and
- Sites without N-sensitive features.

For N-sensitive sites, the case studies included the complete range of atmospheric N input levels, from one of the cleanest sites in the Scottish Highlands (Beinn Dearg SSSI) to examples from areas with high agricultural NH_3 emission densities and for different agricultural sectors. Other sites were selected to enable an assessment of the local enhancement from roads due to high levels of NH_3 and NO_x emissions from vehicles.

Two sites that are not N sensitive were chosen to provide insights for high-density urban environments (Glasgow LEZ) and for farmland, respectively, with the latter designated for bird nesting (Breckland Farmland SSSI). Breckland Farmland is part of a cluster of spatially entangled SSSIs, most of which are N sensitive.

Table 3-13 Local assessments – site categorisation by key types and levels of atmospheric N pressure.

N-sensitivity	Type/level of atmospheric N pressures	Sites
N-sensitive features	Relatively clean sites remote from local emission sources (main atmospheric input from regional/long-range transport/ deposition)	Beinn Dearg, Lough Navar Scarps and Lakes
	High levels of local N input, mainly due to local agricultural NH_3 emission densities (in addition to background levels from a mix of sources)	Breckland Forest, Curran Bog, Ballynahone Bog, Turmennan, Whim Bog, Fenn's, Whixall, Bettisfield, Wem & Cadney Mosses, Dinefwr Estate, Gregynog, Peatlands Park
	High levels of local N input from road transport (in addition to background levels from a mix of sources)	Epping Forest, Ashdown Forest
No N-sensitive features	High levels of local N input from road transport – city centre location with human health concerns	Glasgow Low Emission Zone (LEZ)
	Atmospheric N input not relevant as designated land is agricultural/fertilised soils, designated for bird nesting	Breckland Farmland

N-sensitive sites in relatively clean areas (Beinn Dearg, Lough Navar Scarps & Lakes)

Beinn Dearg, a very remote site in the Scottish Highlands is situated in an area with minor anthropogenic emission sources and represents the site with the least local atmospheric N input of the case study sites considered in this project. Atmospheric N input to the site comes primarily from regional or long-range sources and is characterised by low background levels of NH_3 and NO_2 concentrations. Despite having low N deposition this site still exceeds the lower end of the CL range in the 2017 baseline scenario. Results show that spatial targeting of mitigation measures for this site does not achieve any reduction in local atmospheric NH_3 emissions or concentrations as agricultural emission density is extremely low (< 0.1 kg NH_3 ha^{-1} yr^{-1} for the surrounding 10 km zone). Under the 2030 baseline scenarios, the site is expected to no longer exceed the minimum CL associated with its woodland features. This is due to UK-wide decreases in NO_x emissions, with the local ecosystem benefits largely associated with decreases in long-range transport of oxidised N.

Lough Navar Scarps and Lakes is situated in a less remote location with few very local N emission sources. This results in relatively low background level NH_3 and NO_2 concentrations and N deposition. Locally depositing species account for most of the total N input to this site, with approximately 35% attributed to both livestock emissions and input from wider European sources, in particular, the Republic of Ireland (RoI). With NH_3 concentrations at the site already at relatively low levels in 2017, only small decreases in atmospheric N input are achieved through the higher ambition scenarios. The relatively high importance of emissions from the RoI (>1/3), as illustrated through source attribution data, is indicative of the ASSI's location near the Irish border. National scale mitigation scenarios achieve some decreases in atmospheric N input by reducing regional contributions, and regional/national mitigation efforts in the RoI would further decrease N input. Results show that implementing spatial targeting measures is less efficient in reducing total N input to this site. The exceptions are the optimised scenarios which include substantial UK-wide decreases in mineral fertiliser emissions. These are estimated to result in further decreases, with some parts of the site brought below 1 $\mu g\ m^{-3}$ NH_3.

N-sensitive sites with high agricultural emission densities (Breckland Forest, Curran Bog, Ballynahone Bog, Turmennan, Whim Bog, Fenn's, Whixall, Bettisfield, Wem & Cadney Mosses, Dinefwr Estate, Gregynog, Peatlands Park)

This group of sites is generally characterised by relatively high levels of atmospheric N input, above the critical thresholds for their designated features. N input is mainly due to local agricultural NH_3 emission densities, with varying background levels from a mix of other N emission sources and from sources further afield.

Breckland Forest

Given the location of the site (East Anglia), substantial transboundary influences from mainland Europe and international shipping in the Channel contribute to the long-range input. More locally, agricultural livestock farming, pig and poultry with substantial numbers of broilers, ducks and geese, provides the largest single source of atmospheric N input. The light, sandy and free draining soils of the area are used to grow high-value crops and are suited for outdoor pig rearing. Unlike traditional pig housing, outdoor pig units are not permanently located, with the rearing areas being moved between fields over time, as relatively mobile local NH_3 concentration hotspots.

National scale modelling is assumed to be representative for the wider conditions across the site, however there is some uncertainty associated with quantifying the contribution of pig and poultry farming to the local agricultural emission density, depending on the rearing systems in use locally (see **Annex 5**, Section 3.3.10 for further details). Average NH_3 concentrations across the site decrease with the implementation of spatial targeting measures but remain above the 1 µg NH_3 critical level. High NH_3 ambition scenarios are estimated to result in decreased N deposition, with the optimised scenarios producing the largest reduction.

Local concentration and deposition gradients from individual livestock housed close to the site boundary cannot be captured using a national scale modelling approach. As the site is surrounded by arable farmland with a wide-spread presence of pig and poultry farming, spatial targeting of measures is expected provide benefits to Breckland Forest. Given the prevalence of pig and poultry farms nearby, switching all land spreading to low-emission application or creating low/no N-input zones around the site boundary are expected to provide local decreases in N input gradients into the site.

As the neighbouring SSSI, Breckland Farmland, is not classified as sensitive to atmospheric N input, no spatial targeting measures were applied there. If both neighbouring sites were designated for N-sensitive vegetation, measures applied to a wider area encompassing both sites would provide additional benefit in terms of reduced atmospheric N input across the wider area.

Fenn’s, Whixall, Bettisfield, Wem & Cadney Mosses

This large site straddles the Welsh/English border and is in an area of intense agricultural activity, and livestock emissions are known to be the key atmospheric N issue at the site. Very high agricultural emission densities are observed across the wider region of Cheshire/Shropshire. The livestock sector not only dominates local emissions, but also accounts for >2/3 of local atmospheric N deposition. Local atmospheric N input, in turn, dominates overall N deposition to the site, contributing ca. 80% or more of the total N deposition, depending on the vegetation type.

The 1 km UK-scale model estimates high average NH_3 concentrations (>3 µg NH_3 m^{-3}) for the area surrounding the site, reflecting the density of local agricultural activities. Ammonia concentration estimates for this site varied between 2-3 µg NH_3 m^{-3} with small areas exceeding 3 µg NH_3 m^{-3}. This is largely supported by existing long-term monitoring from the UK National Ammonia Monitoring Network (NAMN), which shows average NH_3 concentrations of ~2.6 µg m^{-3} for the period 1997-2018. However, recent monitoring at the site identified a period of higher NH_3 concentrations in the centre of the SSSI, indicative of the complexity of fine-scale NH_3 emissions and the importance of local sources. Concentration gradients across the site are diluted over a wider area by the UK-scale 1 km grid modelling approach, i.e. within individual 1 km grid squares but also between neighbouring squares. Given the proximity of diffuse and point source agricultural emissions to the boundary of the site, the level of CLe exceedance may be underestimated locally for some areas of the site.

The model results show that the implementation of measures beyond 2030 BAU (WM) scenario are expected to substantially decrease atmospheric N input at the site level. The optimised scenarios are expected to bring most of the site below 2 µg NH_3 m^{-3}.

It is expected that spatial targeting of measures would provide ecosystem benefits to the site. Given the prevalence of cattle farms and poultry manure nearby, switching all land spreading to low-emission application or creating low/no N-input zones around the site boundary is likely to result in local decreases in N input gradients into the site. The site’s location across the border between Wales and England implies that close collaboration between NRW and NE would be required for maximising the potential of spatially targeted measures at this site (Carnell and Dragosits 2015).

Whim Bog

Whim Bog is situated in an area with intensive local agricultural activity including the presence of several large poultry enterprises (above the Industrial Emissions Directive (IED) threshold). There are large numbers of poultry houses within the local area and the estimated resulting agricultural emission densities in the adjacent buffer zones are high. The high density of poultry farms around Whim Bog provides an extreme example illustrating the limitations of the UK-scale modelling approach. Some of these limitations are currently being addressed, e.g. in the continued further development of the underlying models, whereas others are genuine limitations that cannot be resolved, given the current availability of data and information in the UK.

The main points regarding these limitations are:

- The poultry farms in the study area are applying advanced mitigation measures, as required under the IED, i.e. Best Available Technology. Many of the poultry houses are, for example, equipped with belt systems for manure removal that are frequently cleaned, and much of the manure is exported from the area to further afield (loaded directly from the belts in a clean operation). Therefore, given current practice, estimated emissions using national average emission factors are likely to result in an overestimate of local concentrations.
- Poultry emission factors – Current emission factors for laying-hen housing, as applied in the UK agricultural emission inventory model and therefore also in this project, are not representative of more modern housing systems such as enriched and colony cage systems, single-tier and multi-tier free range systems. New emission factors for these housing types have been derived based on more recent measurements (Defra AC0123[13]). These will be applied in the next iteration of the UK emission inventory during 2020, with a revised emission reduction factor applied to in-house poultry litter drying systems (increased from 30% to 60% reduction). These new housing emission factors are lower than those representing the older laying-hen systems (by 30 – 70%). Therefore the model estimates presented in this study are very likely resulting in further overestimation of emissions from the local farms, based on both this outdated emission factor and the use of average emission factors across all poultry housing systems in the UK-scale modelling (see previous paragraph).
- A previous landscape scale case study included both detailed monitoring of atmospheric NH_3 concentrations over 18 months (2007-2008) and modelling of emission sources, concentrations and N deposition for a 6 km by 6 km area including Whim Bog (Vogt *et al.* 2013). This study confirmed that using the UK inventory emission factors and assumed average practice for laying-hen enterprises leads to overestimates in emissions. It also confirmed that, with the prevailing wind in the area, the plumes from the poultry farming activities are mostly blown away from the bog rather than towards it. It illustrated very clearly how the UK-scale modelling aggregates and smooths out the individual emission sources located across the fields and farms in each 1 km grid cell, with a large number of poultry houses (layers) and extensive upland sheep and cattle farming.
- The high-resolution emission model used to create the 1 km by 1 km grid data (AENEID, see **Annex 4** for detailed description) uses a statistical approach to estimate local emissions, by combining high-resolution agricultural statistics (at a parish level) with land cover and agricultural practice information and emission factors. This approach generally works well for diffuse emission sources, such as landspreading of manures, mineral fertiliser applications and livestock grazing. For livestock housing and associated manure storage emissions, this approach dilutes and smooths out what are often local “hotspots” in the landscape However, this is the best available, given the limitation of spatial location data across the UK.
- A further limitation is related to the data licensing agreements for using detailed data. These agreements require information from at least 5 holdings to be combined to protect the confidentiality of these datasets and to meet the non-disclosive requirements for any output.

Notwithstanding the limitations and caveats associated with the national datasets applied for the unusual case of the distinct emission sources surrounding Whim Bog, this case study provides a good example why and how spatial targeting of measures is an appropriate strategy for N-sensitive designated sites in high-density emission areas. The assessment illustrates how important it is to take into account local concentration gradients above the wider regional background at a landscape scale and to include detailed information on local practice in use and mitigation measures already in place.

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[13] Unpublished.

Dinefwr Estate

The source attribution data (5 km grid resolution) identify the main contributors to N deposition at the site, with local knowledge supporting the importance of agricultural emissions sources in this area. The emission density dataset cannot be shown for sites in Wales, as the spatial detail on holding locations available is not sufficiently detailed (see **Annex 5**, Section 2.1 for details). However, it can be confirmed from the data available that the key agricultural sectors in the area are beef, dairy and sheep farming. Aerial photography confirms that there are several cattle farms located within 1-2 km from the site.

The results of UK-scale modelling show concentrations of 1-2 µg NH_3 m^{-3} for most of the wider area surrounding the site. These modelled concentrations appear to be on the low side, given local data on lichen (Bosanquet 2019[14]) and reports of strong slurry smells across the site on numerous occasions. With the local sources (at the 1 km scale) relatively close to the site boundary, such as cattle houses and related manure/slurry storage and spreading, spatial targeting scenarios should result in overall decreases of maximum and average NH_3 concentrations. However, modelled values remain above the 1 µg m^{-3} critical level for NH_3. It is very likely that local concentration gradients are smoothed out across the wider area at the 1 km grid resolution, and local concentration monitoring at several points on the boundary and towards the centre of the site would provide further insights. The relative importance of cattle emissions to atmospheric N input at this site is emphasised, with the highest ambition cattle scenarios producing the greatest decreases at this site.

Spatial targeting of measures, especially those relevant for cattle farming, is expected to decrease local concentration gradients. From the modelling results, it would be important to include sources within the wider area due to higher agricultural emission density 3-10 km from the site boundary. Without inclusion of broader measures, the regional background is likely to continue to affect the designated features.

Gregynog

This site is in an area of intensive agricultural activity, and emissions from this sector are known to be the key atmospheric N pressure at the site. The 5 km grid resolution source attribution assessment identifies the main contributors to N deposition at the site, with the primary input being livestock emissions and > 60% of atmospheric N input attributed to local sources. For the site's specific situation and the sensitive lichen community, the accurate assessment of local NH_3 concentrations may be more important than atmospheric N input through deposition. The emission density dataset cannot be shown for sites in Wales, as the spatial detail on holding locations available is not sufficiently detailed (see **Annex 5**, Section 2.1 for details). However, it can be confirmed from the data available that the key agricultural sectors in the area are beef, poultry and sheep farming. The area is well known for large numbers of smaller poultry farms that together form a substantial source of NH_3 emissions. Given the relatively recent establishment of many of these farms, it is possible that their emissions are not yet fully represented in the national agricultural emission inventory, due to time lags involved with various sequential data collection and inventory preparation stages.

Nevertheless, national scale modelling overall reflects this local knowledge of an intensive agricultural area, with relatively high NH_3 concentrations observed to the east of the site. All the scenarios beyond the less ambitious 2030 BAU (WM) baseline are expected to result in additional decreases in atmospheric N input at the site itself, however average NH_3 concentrations remain above the 1 µg m^{-3} critical level.

Local concentration gradients at this site may be mitigated with spatial targeting measures, which are expected to produce declines in NH_3 concentrations and N deposition. However, if

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[14] Bosanquet S. (2019). *Twig Lichens at Dinefwr Park SSSI and Gregynog SSSI revisited in 2019*. Natural Resources Wales Report. 18pp.

the sources in the wider area are not included in efforts to reduce NH_3 emissions, the regional background is likely to continue to affect the designated features.

Curran Bog and Ballynahone Bog

These two bogs are located in close proximity to each other, embedded in lowland agricultural landscapes with high emission densities. In terms of atmospheric N input, they are characterised by dairy and beef farming, and pig and poultry, the latter particularly near Ballynahone Bog. Several years of NH_3 concentration measurements at Ballynahone Bog show spatial variability in NH_3 concentration across the ASSI, with the western part close to local emission sources, frequently showing high monthly NH_3 concentrations (see **Annex 5**). In contrast, another sampler located near the eastern edge of the bog, approximately 1-2 km further away from the main local sources, shows on average the lowest concentrations measured for the bog. No current NH_3 concentration measurements are available for Curran Bog. There are however plans to establish several sites following the current lock-down due to COVID-19.

The higher measured concentrations described above are due to two main reasons:

- Two farms are located very close to the site boundary, with local concentration gradients from livestock housing and manure storage extending into the bog, and gradients confirming decreasing concentrations with distance. Another sampler closer to the other local source also shows elevated NH_3 concentrations. These processes of dispersion and dilution of emission plumes from very local sources cannot be captured by the 1 km grid resolution modelling approach. Local scale modelling is in progress under a different project, but full results will not be available until 2021.
- The UK-scale spatial modelling carried out under this project, at a 1 km grid resolution, uses the best available high-resolution agricultural emission maps (see also **Annex 4** for a more detailed description of the methodology). These are derived from aggregated zonal statistics (approx. 5 km grid areas), using a statistical approach that spatially distributes emissions calculated for the livestock population and crop/grass areas present based on land cover data. This approach was designed to meet the strict disclosive criteria for use of the high-resolution June agricultural survey statistics and has been shown to work well, on average. This is especially the case for distributing diffuse emission sources, such as land spreading of manures, mineral fertiliser application and livestock grazing, across the wider landscape. In the absence of more detailed data that could be used for the high-resolution UK-scale modelling, the current estimates are the best available. However, in reality, larger farms are individual emission “hot spots” in the landscape, for livestock housing and associated manure storage emissions. These individual farm emissions are necessarily more diluted and dispersed across the wider area, due to the restrictions on how the model input data can be used.

For Ballynahone Bog, the modelled emissions resulted in smoother concentration and dry deposition patterns than expected for the combined reasons of input data resolution and model grid cell size. It should also be noted that the modelling approach does not consider the inter- and intra-annual variability of NH_3 concentrations, which are evident from long-term monitoring at this site (see **Annex 5**).

Spatial targeting of measures, as modelled in the current project are estimated to achieve reductions in NH_3 concentrations with the higher ambition and optimised scenarios being the most effective. The modelled concentration decreases are not estimated to be sufficient to bring the sites below the 1 $\mu g\ m^{-3}$ critical level for NH_3 and the critical loads threshold, due to the continued high agricultural emissions densities in the wider surrounding area. A separate modelling exercise, carried out for DAERA (unpublished), applied high-ambition Northern Ireland-wide measures (25% emission reduction for agricultural NH_3, with additional smaller spatial targeting measures). A key message from this work is that the measures reduce NH_3 concentrations and N deposition considerably from a very high baseline but are by themselves not sufficient to achieve widespread decreases in the number of sites exceeding critical loads and levels. However, it is expected that targeted local measures, especially for situations such as Ballynahone Bog with very local sources, could make a substantial difference, in combination with country-wide measures to decrease wider background concentrations and deposition.

Turmennan

Turmennan is a small designated site located in an agriculturally intensive region with many pig farms in the vicinity and a high number of agricultural sources within several kilometres' distance. Source attribution assessment accurately reflects local knowledge that the main atmospheric N inputs to the site are local input from livestock emissions. Notably for Turmennan, and in contrast to many other sites considered in these local scale assessments, NH_3 concentrations are expected to decrease to approximately 2 µg NH_3 m^{-3} from the 2017 baselines towards the 2030 NAPCP+DA scenario. However, NH_3 concentrations are predicted to remain above the 1 µg critical level for all more ambitious UK-wide and spatially targeted scenarios, with the latter resulting in small further decreases in NH_3 concentrations and N deposition to the site.

Peatlands Park

This site was assessed for local influences of both agricultural and road transport emissions. Peatlands Park is located in an intensive agricultural area with cattle and poultry farming. Modelled NH_3 concentrations in the surrounding area are high, in keeping with local knowledge. Current ongoing work by UKCEH to establish a new network of NH_3 measurement across the site has estimated gradients of high concentrations from potential sources close to the site boundary in the west, north and east and lower concentrations towards more central locations. The 5 km source attribution data indicate that local sources provide most of the atmospheric N input to Peatlands Park ASSI, with emissions from livestock accounting for > 70% of locally depositing species. The mitigation scenarios modelled in this project are expected to bring the maximum modelled NH_3 concentration at the site below the 3 µg m^{-3} NH_3 CLe., but concentrations are expected to remain above the 1 µg m^{-3} NH_3 CLe in all scenarios.

Scenarios with high ambitions for NH_3 achieve the greatest decreases across the ASSI, indicating the effectiveness of broader national/Northern Ireland-wide measures. N deposition to the site is estimated to decrease by several kg N ha^{-1} yr^{-1} under the most ambitious scenarios. It is, however, expected that spatial variability within the 1 km grid cells of the UK-scale modelling hides larger potential improvements to areas closer to the centre of the site, with the site's outer perimeters acting as a buffer zone for the core area. NH_3 concentration monitoring will be commissioned by DAERA soon and is expected to bring further clarity on the finer gradients and magnitude in NH_3 concentrations at the site. This should shed light on the expected complex spatial variability across the site which contains some potentially sheltered areas contrasting with areas closely bordering emission sources. This information can then be assessed against the 1 km grid baseline modelling for further conclusions to be drawn.

The M1 passes close to Peatlands Park but is 70 m away from the site boundary. At this distance, the effects of local traffic emissions are significantly diminished and including this localised effect is expected to have very little effect on the overall conclusions for the site.

N-sensitive sites with road transport as the main atmospheric N pressure (Ashdown and Epping Forest)

The key atmospheric N pressures vary across Ashdown Forest and Epping Forest. The parts worst-affected by N deposition are close to roads, where local road traffic is the single largest contributor. However, at greater distance from roads, where the localised effects diminish, the area-average and area-total N deposition fluxes are not dominated by road traffic. The local case study for Ashdown Forest used modelling on both a 1 km x 1 km and a 2 m x 2 m resolution, whereas the Epping Forest study also included transects of location-specific predictions.

At Ashdown Forest, road transport is estimated to contribute only 12% of the N deposition to the site overall (5 km source attribution data), but local modelling for the worst-affected part of the site estimates road transport contributions of 55% of N deposition to woodland. The emission reductions predicted between the 2017 and 2030 baseline scenarios cover a range of sectors, including road transport, and so improvements are predicted to occur over the whole site, including the worst-affected roadside locations. Similarly, so long as post-2030 NO_x measures use zero exhaust emission vehicles rather than an increased use of vehicles equipped with petrol engines, the higher ambition UK-wide and spatially targeted scenarios predict further improvements to both area-average and area-maximum deposition fluxes.

At Epping Forest, the location-specific predictions illustrate the effects of local enhancement close to roadside verges, with much higher local NH_3 concentrations than the 1 km grid average values (as high as 4 $\mu g\ m^{-3}$ in 2017; potentially increasing to above 5 $\mu g\ m^{-3}$ by 2040, depending on the assumptions on future vehicle fleet composition). Local scale modelling predicts that maximum NO_x concentrations decrease from 152 μg^{-3} in 2017 to 41 $\mu g\ m^{-3}$ by 2040. Conditions at the roadside are thus very similar for Ashdown Forest and Epping Forest. The 1 km grid model results agree with the local assessment in that both models predict continued exceedances of the NH_3 critical level and the N deposition critical loads. Well away from roads, where deposition fluxes are much smaller, road traffic contributes much less to the total N deposition, and because the majority of Epping Forest, by area, is further than 200 m from any road, the area-average and area-total N deposition fluxes are not dominated by road traffic. The degree to which the CLe and CL are exceeded, and in some cases whether they are exceeded at all, is therefore a direct function of the spatial resolution of the model. As a general rule, using a finer-resolution model for local-scale assessment will, by definition, give different results unless the site is distant from any concentrated emissions source.

For both sites, targeted measures focusing on agricultural NH_3 are expected to have very limited effects on either the area-average or the area-maximum fluxes, due to the relatively low agricultural emission density in the wider area.

Non-N-sensitive sites with road transport emissions as main pressure (Glasgow LEZ)

There are no sensitive designated features in the Low Emission Zone (LEZ), therefore CL/CLe assessment is not relevant. The road transport modelling suggests that the annual mean NO_2 objective set for the protection of human health will be achieved under the 2030 NAPCP+DA baseline scenario and all other future-year scenarios tested. Local emissions from road traffic and other urban sources, are very important to air quality in the Glasgow LEZ. Thus, measures which assume blanket reductions in NO_x emissions have a positive effect on predicted annual mean NO_2 concentrations. Location-specific air quality predictions cannot, however, be made directly from 1 km x 1 km resolution model outputs.

Other non-N-sensitive sites (Breckland Farmland)

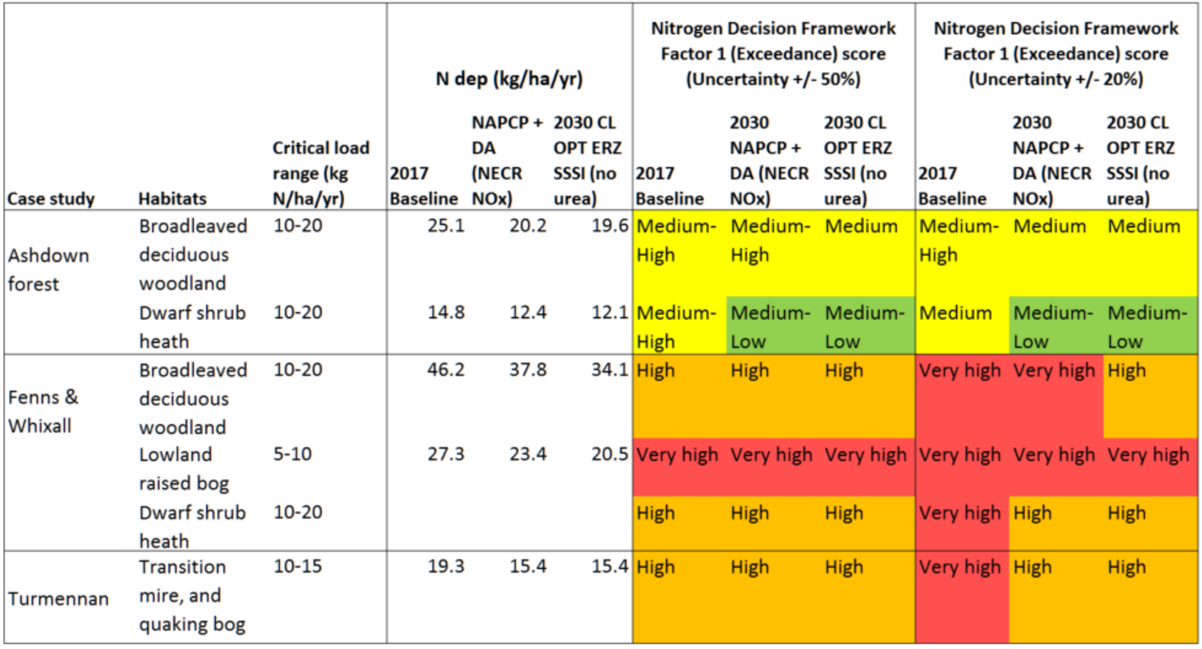
Breckland Farmland forms part of a network of designated sites in eastern England. This site is designated for protecting a rare bird (Stone curlew) and contains mainly managed agricultural crop areas that receive mineral and organic fertilisers. Therefore, atmospheric N input is not expected to be a threat to N-sensitive habitats here. UK-scale 1 km grid resolution modelling of mitigation scenarios results in minor changes to NH_3 and NO_x concentrations, as well as N deposition, from a combination of national measures and spatially targeted scenarios at other nearby SSSIs.

As this site is classified as not sensitive to atmospheric N input, no spatial targeting measures were applied in the modelling. However, any N sensitive low-growing semi-natural vegetation at the site would benefit from the measures applied to the adjacent and spatially entangled Breckland Forest SSSI. The exception is the EDZ scenario, where the measures designed to protect Breckland Forest resulted in additional landspreading closer to Breckland Farmland, thereby increasing NH_3 concentrations and localised N deposition. This relatively unusual example highlights that, if such measures were to be implemented in practice, care would have to be taken to define locally suitable zones for displacing the additional landspreading materials, rather than just imposing blanket concentric zones. If, however, both neighbouring sites were designated for N-sensitive vegetation, measures applied to a wider area encompassing both sites would provide additional benefit in terms of reduced atmospheric N input across the wider area.

Nitrogen Decision Framework

Three case studies were selected, representing a range of N sources and receptor habitats, to see how the ecological risk from national data (Factor 1 Exceedance score) changed with mitigation scenarios (Table 3-14), and with different assessments of the level of uncertainty in N deposition. Where the critical load for habitats was dramatically exceeded (Broad leaved deciduous woodland and Lowland raised bog at Fenn's and Whixall), decreases in N deposition as a result of the emissions scenarios did not change the Exceedance score. Where N deposition lay within or close to the critical load range (Dwarf shrub heath at Ashdown forest) a drop in the deposition under the more ambitious mitigation *2030 CL Opt ERZ SSSI (no urea)* scenario resulted in an improvement in the Exceedance score. Factoring in a lower level of uncertainty in N deposition (dropping from +/- 50% to +/-20% in the assessment), due to the finer resolution modelling of N deposition, did alter the NDF risk scores even though the N deposition numbers remained unchanged. In some cases, the NDF risk score increased (Broadleaved deciduous woodland at Fenns and Whixall), in others it decreased (Transition mires and quaking bogs at Turmennan). This is because the NDF assessment takes into account uncertainty in the deposition as well as other sources of uncertainty in evaluating ecological risk. This emphasises the importance of accounting for uncertainty in the deposition, and the value of site-specific modelling of N inputs.

Table 3-14. Nitrogen Decision Framework (NDF) outcomes for selected case studies and scenarios.



			N dep (kg/ha/yr)			Nitrogen Decision Framework Factor 1 (Exceedance) score (Uncertainty +/- 50%)			Nitrogen Decision Framework Factor 1 (Exceedance) score (Uncertainty +/- 20%)		
Case study	Habitats	Critical load range (kg N/ha/yr)	2017 Baseline	NAPCP + DA (NECR NOx)	2030 CL OPT ERZ SSSI (no urea)	2017 Baseline	2030 NAPCP + DA (NECR NOx)	2030 CL OPT ERZ SSSI (no urea)	2017 Baseline	2030 NAPCP + DA (NECR NOx)	2030 CL OPT ERZ SSSI (no urea)
Ashdown forest	Broadleaved deciduous woodland	10-20	25.1	20.2	19.6	Medium-High	Medium-High	Medium	Medium-High	Medium	Medium
	Dwarf shrub heath	10-20	14.8	12.4	12.1	Medium-High	Medium-Low	Medium-Low	Medium	Medium-Low	Medium-Low
Fenns & Whixall	Broadleaved deciduous woodland	10-20	46.2	37.8	34.1	High	High	High	Very high	Very high	High
	Lowland raised bog	5-10	27.3	23.4	20.5	Very high	Very high	Very high	Very high	Very high	Very high
	Dwarf shrub heath	10-20				High	High	High	Very high	High	High
Turmennan	Transition mire, and quaking bog	10-15	19.3	15.4	15.4	High	High	High	Very high	High	High

3.3.2 Analysis of assessments, reflecting on feasibility, constraints, co-benefits and trade-offs

A key question for the local assessment case studies to resolve is whether UK-scale modelling approaches (at a 1 km and 5 km grid resolution) can be used to capture local issues. This question needs to be answered separately for several different but related datasets:

The **5 km grid source attribution dataset** (last updated for the year 2012) overall identified the main contributing factors to N deposition across all sites with relevant semi-natural vegetation features (using average data across the site). It also showed the expected partitioning between local and more long-range N deposition, wet/dry and reduced/oxidised N. There are two main limitations with this dataset:

- Local pollution gradients (e.g. from individual livestock houses or busy roads close to the site boundary) cannot be captured using this 5 km grid resolution approach. Larger contributions from the transport sector > 10% are sometimes used to screen for likely large road transport influence, but in practice, any site which is close to a busy road has the potential for locally-elevated transport influences (Dragosits *et al*. 2015). Similarly, for large intensive livestock operations close to a designated site's boundary, the actual local gradient and its relative importance cannot be captured. However, all of the sites assessed in this study (or any other studies on UK designated sites carried out, to the authors' knowledge) where agricultural emissions provide substantial atmospheric N input, have been correctly identified as such by the source attribution data.
- The dataset is now not considered up to date, and any new emission sources established since 2012 or removed/mitigated (across all sectors, for both NH_3 and NO_x), could lead to false negative or false positive assessments, depending on local circumstances.

The **agricultural emission density assessment** overall identified key agricultural sectors dominating the local area surrounding all designated sites, and also provided a useful indicator of the magnitude as well as relative proportion between local source types. The only site where this dataset is less useful while still providing a clear indication of the key sources, is Whim Bog. This site is perhaps unique in the UK in terms of the local density of poultry populations in a relatively small area, which magnifies the uncertainties of using the same average emission calculations as in the UK agricultural emission inventory rather than taking local management practice and systems into account. This is not currently possible with available UK data sources. For Wales, the data with locations only provided at the parish level rather than for individual holdings, were not suitable for calculating agricultural emission densities for 2017. This was only realised by the team late in the interpretation stage of the data. However, more detailed locational data exist, and earlier versions were used for previous work for NRW (see Carnell & Dragosits 2015). Therefore, site profiles for Dinefwr Estate and Gregynog do not contain full emission density assessments, with less quantitative descriptions of key agricultural sectors provided instead. This does not affect the UK-wide 1 km grid resolution emission modelling, which uses an area-based approach, rather than individual farm locations, to distribute emissions by land cover weighting, resulting in non-disclosive emission maps.

The **1 km grid resolution UK modelling** represents average conditions across all sectors, in terms of the underlying emission modelling. In practice, this means that agricultural emission factors are averaged out across each of the four countries (e.g. England-specific, Wales-specific data, *etc*.) and take account of existing agricultural practice or mitigation only at this level. Therefore, any specific implementation of practice or mitigation measure at a local level cannot be represented in more detail. Similarly, the 1 km grid resolution cannot adequately represent steep local concentration gradients away from local sources (especially point or line sources, such as larger livestock houses or busy roads), and therefore will not show local enhancements at a true local/landscape scale of fields, farms and semi-natural land. For some sites, where this local enhancement is a critical factor (e.g. Ballynahone Bog, Epping Forest), the 1 km grid representation of the mitigation scenarios will not adequately show the threat or the potential for improvements, both due to the dilution of any very local measures across the wider grid square and the model may not able to capture local practice, compared with average conditions. For example, if a measure (or set of measures) is modelled with a 70% implementation rate across all dairy farms, this is then diluted across all relevant farms, thereby smoothing patterns locally. For enhancements of both NH_3 and NO_x concentrations and dry deposition close to the roadside edge, there is a large difference in expected impacts from road transport compared with the 1 km grid resolution data, and this was quantified in detail for all case studies where road transport emissions are a significant source of atmospheric N input.

Nitrogen Decision Framework

The Nitrogen Decision Framework (NDF) results show that at sites where the N deposition is within or near the critical load range, there is scope to reduce the ecological risk score. If applying the NDF in full, this would be complemented by an assessment of potential impacts on-site (the Factor 2 score) (Jones *et al.* 2016). The results show that taking account of the reduced uncertainties around the N deposition component due to finer resolution and site-specific modelling makes the NDF score more sensitive to changes in mitigation scenarios. There is scope for further improvement in the assessment. For example, additional information on the location of sensitive habitats within the site, coupled with detailed spatial modelling of deposition would make this a much more sensitive tool.

Summary of insights from UK, country and local scale assessment

The national scale modelling (UK and DAs) and local scale case studies provided a testbed for assessing types of designated sites that would benefit from spatial targeting of mitigation. The results show that the answer depends on the characteristics of the site and key emission sources of atmospheric N to the site. Section 3.2.1 (Table 3.11) provides an overview of three main types of N-sensitive sites:

- **Sites remote from local emission sources** – such sites are often relatively clean in terms of atmospheric concentrations of NH_3 and/or NO_x but may still receive substantial regional or transboundary N deposition levels, which may exceed the site relevant critical loads. For such sites, the main policy drivers are wide-ranging national and international emission mitigation, such as the current NECR/NECD targets. For UK sites located close to international borders, i.e. the Republic of Ireland for Northern Ireland, bilateral engagement on transboundary air pollution impacts could establish mutual benefits for designated sites on both sides. In this particular case, such engagements might end up focusing on local benefits more than on long-range transboundary processes in the true sense of this definition.
- **Sites that are subject to high levels of local N input from road transport** – at such sites (e.g. Epping Forest), where sensitive habitats are located adjacent to emissions sources, these emissions drive the site-maxima and the most effective mitigation measures are likely to involve targeting the individual roads running through each site. Without addressing these site maxima, the site cannot be brought within the critical levels and critical loads, (even though at the 1 km grid resolution results may show that the critical levels and loads are achieved). Because concentrations and deposition fluxes at the worst-case locations are driven by emissions from local roads, it will be challenging to remove these effects without addressing emissions from these roads. Road traffic mitigation is complicated by many factors, including the need to avoid the re-routing of polluting vehicles into other sensitive areas. As was noted for the Ashdown Forest case study, local-scale traffic modelling can provide a helpful indication of the origin and destinations of journeys affecting the sites and this may allow specific local targeting of traffic-related mitigation measures. Because vehicle emissions are so important to N deposition at the roadside, fleet composition will be a key factor for N deposition at these sites in the future (e.g. petrol vs electrification or the level of modal shift achievable locally). Because vehicle emissions, particularly those of NH_3 and regardless of uncertainties regarding these emissions, do not dominate the national total, the composition of the future vehicle fleet is of less relative importance nationally.
- **Sites that are subject to high levels of local NH_3 emissions from local agricultural sources** – the spatial targeting measures and scenario tested in the UK-scale modelling work carried out in this project largely focused on this type of sites. In principle, the same concept as laid out for sites affected by high levels of local transport, applies to agricultural sources: local concentration and deposition gradients from nearby sources such as large livestock houses or manure stores affect sensitive vegetation through enhancement above the local background. This can potentially cause acute damage.by high concentrations during shorter periods, as well as longer term accumulation. Spot-reducing such sources through spatial targeting is expected to be highly effective, as it can decrease both acute as well as longer term atmospheric inputs. However, with most of the UK's NH_3 emissions originating from agriculture, it is not just such local hotspots where mitigation is required to benefit N sensitive habitats and sites. Local and regional agricultural emissions are, in combination, responsible for the wider elevated background concentrations above the critical levels and the related local dry deposition of reduced nitrogen compounds. Therefore, spatial targeting of measures over a wider area of mixed agricultural point and diffuse NH_3 sources can be effective in decreasing atmospheric N input more widely in the local area, through sets of measures implemented in Emission Reduction

Zones (ERZ) and Emission Displacement Zones (EDZ). In addition, recapture of emissions from point sources e.g. livestock houses, manure/slurry stores, using specifically designed tree belts, planted and managed longer-term can also be useful as a secondary mitigation measure. However, such tree belts take time to grow to their optimal condition and require maintenance to remain effective. They do not provide immediate benefits of primary technical measures, such as low emission manure spreaders or scrubbers that reduce emissions at source as soon as they are installed.

The effectiveness of the modelled spatial targeting measures varies between sites. This is due to the make-up and density of the emission source sectors near each site and the ability to influence concentrations or deposition at sites through the bundle of measures tested. The results also clearly illustrate, despite the scale issues and resulting smoothing out of local gradients/enhancements, that targeting zones surrounding sites is the most efficient solution for implementing measures to reduce NH_3 concentrations and dry NH_x deposition, per unit of emission reduction. At a site level, targeting measures within buffer zones can be almost as effective as applying measures UK/DA-wide, in terms of reductions in dry NH_x deposition.

In summary, there is no single “one size fits all” spatial targeting scenario that will be the most effective approach to maximise environmental benefits for all designated sites. However, the concepts of ERZ and EDZ can be used across all sites where local sources substantially impact N-sensitive designated sites. This is provided that these concepts are implemented with types, ambition levels and implementation rates of measures that are both applicable and deemed effective for local sources. Such measures, in combination with UK (or DA)-wide measures, would provide environmental benefits across large numbers of designated sites, as laid out with the example scenarios modelled in this project. In this context, a substantial impact of implementing the NAPCP (with modifications to suit the Devolved Administrations) and meeting the NECR targets UK-wide is expected, through the combined effects of both NH_3 and NO_x emission mitigation, from measures implemented across the country (and across the wider European continent). The *2030 NAPCP+DA (NECR* NO_X*)* baseline scenario, as set out to meet the NECR commitments, is estimated to achieve the UK Government’s Clean Air Strategy target for England, with a 19% decrease in N deposition onto protected sensitive priority habitats between 2016 and 2030[15]. Similar decreases are modelled for the UK as a whole, at 18.4%, 18.7% for Wales, 18.6% for Scotland and 17.9% for Northern Ireland.

3.4 Optimised strategy for spatial targeting of mitigation to maximise environmental benefits

3.4.1 Outline of optimised strategy

The assessment of a selection of UK-wide and spatially targeted mitigation scenarios, across a range of ambitions and scales, as laid out in the previous sections, has shown that an optimised mitigation strategy needs to consider a nested approach for maximising the effectiveness of mitigation measures for the benefit of N-sensitive habitats and designated sites. This includes the following main strands:

- **Implementation of UK-wide measures (with appropriate adaptation by the DAs) or similarly ambitious DA-led measures to decrease NH_3 and NO_x emissions** - resulting in substantial decreases in atmospheric N concentrations and N deposition and decreasing exceedance of critical thresholds. This will lead to improved conditions for sensitive habitats and species in both source areas (with high concentrations and deposition) as well as in more remote areas (e.g. upland/mountain areas with a large

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[15] See Section 3.2 for details – the definition of “protected priority sensitive habitats” remains under discussion by JNCC and Defra, so this study has used the set of priority habitats that are currently reported in the annual Trends Report (Rowe *et al*. 2020).

input to N deposition from precipitation) where long-range deposition will be reduced. In some parts of the UK, binary exceedance-based metrics (i.e. exceeded vs not exceeded) are expected to decrease more slowly, as current atmospheric input decreases from very high baselines – this is especially the case in areas with high agricultural emission densities. However, more nuanced environmental benefit metrics, such as excess nitrogen (i.e. the amount of atmospheric N input above a habitat's critical load), will enable tracking of progress against targets. Measures that lend themselves to UK-DA-wide implementation include a mix of regulatory approaches, payment schemes for environmental benefits and best practice guidance. Regulatory approaches could be related to mineral fertiliser types, such as mandatory additives such as inhibitors, or replacement of urea/UAN based fertilisers, and/or Best Available Technology type measures for large cattle farms. Examples for payment schemes for environmental benefits are the new Environmental Land Management Scheme (ELM) currently being developed for England, and DA equivalents. Some measures are already under way, whereas others are still in consultation or under development, across the DAs, both towards meeting 2030 targets (e.g. NECR, NAPCP, CAS) or with longer terms (e.g. the UK Government's 25 Year Plan). The Plan specifically mentions:

  - low-emission manure storage and landspreading of manures, with reference to the Farming Ammonia Reduction Grant (FARG) Scheme for slurry store covers;
  - good nutrient management practice;
  - putting in place a robust framework to limit inputs of N-rich fertilisers (both mineral and organic) to economically efficient levels;
  - introducing clear rules, advice and, if appropriate financial support; and
  - encouraging the use of low-emission fertilisers (and reviewing take-up via the British Survey of Fertiliser Practice (BSFP).

- **Spatial targeting locally where appropriate** – "spot-reducing" high atmospheric N concentrations and localised deposition near designated sites has been shown to be more effective for achieving benefits locally than the same amount of emission reduction spread more widely across the country. This specifically reduces maximum concentrations and deposition along local air pollution gradients, i.e. local enhancement above the wider regional background. This applies to both NH_3 and NO_x sources, and across all emission sectors. As summarised in Section 3.3., it is unlikely that a single "one size fits all" spatial targeting scenario will be the most effective approach to maximise environmental benefits for large numbers of designated sites. For spatial targeting to be successful, both in terms of the magnitude of environmental benefits and local engagement, a clear framework for identifying priority actions needs to be in place, with a list of potential options that can be selected for optimal local outcomes. Such a flexible framework could recommend both emission reduction measures and emission displacement measures, depending on local circumstances. An important consideration is whether displacing emissions to a greater distance from the site under consideration would negatively impact on other nearby designated sites or sensitive priority habitats. In general, emission reduction measures result in reduced atmospheric N input both locally and for the wider region/transboundary. However, in some situations local emission hotspots may benefit from being moved away from site boundaries, or de-intensification to a lower emission use of land next to the site.

In summary, an optimised strategy is expected to combine/nesting both approaches, i.e. using a mix of well understood and effective measures more widely at the UK/DA level, as well as specific targeting, depending on local emission source types and conditions, agricultural management systems/practice in place and opportunities for further improvement, by engaging locally.

As has been illustrated with the different types and spatial resolution/detail of modelling and assessment undertaken in this study, it cannot be over-emphasised how important local/'on-the-ground' information is compared with relying on national datasets (even detailed ones), especially at any decision making stages. Contributions to atmospheric N input, especially for agricultural NH_3, from sources in the vicinity of designated sites may vary considerably, depending on some or all of the following issues:

- Correct information on spatial location of sources - Agricultural holdings are not located exactly in the high-resolution datasets, with locations often based on e.g. post codes which may cover large areas in sparsely populated rural areas; there are no existing datasets on the location of potential sub-sources such as manure storage facilities which may be purpose-built slurry tanks or field heaps separate from e.g. livestock houses.
- Information on local agricultural management practice/activities/systems is essential for identifying suitable measures for spatial targeting of mitigation. For example, if there is much prior implementation of low-emission measures in an area, these need to be a) accounted for as part of the assessment of the threat of atmospheric N and b) taken into account when optimising mitigation strategies; soil conditions may be unsuitable for injection of slurry; existing systems may or may not allow retro-fitting of measures, which has implications on time scales and costs of their potential suitability. For large pig and poultry farms regulated under the IED, prior implementation of Best Available Technologies measures can be assumed, but at different levels, e.g. due to the timing of their permit applications, and/or estimated impacts during the permitting process.
- Local wind conditions at a site may differ considerably from prevailing conditions and contrast with wider regional patterns, e.g. due to topography, land-sea circulation patterns and similar. Such local patterns cannot be represented in national-scale modelling approaches and need local data or knowledge for designing locally optimised solutions.

3.4.2 Cost-benefits of the strategy in relation to emission targets (e.g. NECR) and environmental benefits for ecosystems, priority habitats and designated sites

Using the current best cost estimates available, reducing NH_3 emissions to meet the NECR targets in the 2030 NAPCP+DA baseline scenario was estimated to cost approx. £159 M per annum in a UK-wide context (see **Annex 4**, Section 2.6 for details). The results in this project show that spatially targeting mitigation measures close to designated sites provides additional value compared with the same amount of emission reductions spread widely across the country.

This approach maximises the impact of a given emission reduction and its costs. Prioritising the implementation of UK-wide mitigation measures close to designated sites initially could also lead to much faster improvements at the sites, if there is a slow roll-out of UK-wide measures over a longer period. This smarter approach can therefore be used both for prioritising measures that will be rolled out UK (or DA) wide, as well as putting more ambitious additional measures in place where most needed. While spatial targeting of measures can in principle be applied to priority habitats, the approach is perhaps easiest to implement for designated sites, as they have clear boundaries in the landscape and the implementation of measures can be quantified and tracked more easily.

Table 3-15 provides an indication of the overall costs to implement the agricultural components of the mitigation scenarios. Overall, the agricultural measures of the optimised scenarios are costed at > £90 M more per annum more than the 2030 NAPCP+DA baseline (NECR NO_x), with most of the additional annual cost (> £60 M) associated with England, nearly £20 M with Northern Ireland, £7 M with Wales and nearly £5 M with Scotland. The relatively higher costs associated with Northern Ireland are due to the larger agricultural NH_3 emission sector, compared with Wales or Scotland. The cost of the optimised scenarios was calculated by combing the costs of the measures that were modelled, i.e. the higher ambition measures implemented in the variable sized ERZ and the EDZ, with the urea/UAN replacement being deemed, on average, cost-neutral, compared with the inhibitor cost. Overall, the UK costs associated with optimising critical levels are slightly higher than for critical loads, by £1.8M or 0.7% of the cost of the CLe optimised scenario of £253M per annum.

For the UK-wide and spatially targeted scenarios, costs increase, as expected, with increasing ambition of measures as well as with increasing widths of ERZ. Given the larger number and wider geographic spread of SSSIs compared with SACs, it follows that implementing the same ambition of measures in 2 km zones around SACs would cost less than for SSSIs. The costs of implementing the EDZ scenario are relatively small in comparison to the other mitigation scenarios, especially given the marked impact the scenario is estimated to have in terms of reducing CLe exceedance.

Table 3-15. Total estimated cost (£ million per annum) of each agricultural NH_3 emission scenario. Costs of spatially targeted scenarios have been estimated based on the UK-wide implementation (see Section 1.4.5 of Annex 4 for full details of how these costs have been estimated, Section 6).

Country	England	Wales	Scotland	NI	UK	Difference to NAPCP+DA (UK)
2030 BAU (WM)	27.0	2.0	3.2	6.5	38.7	n/a
2030 NAPCP+DA (NECR NOx)	109.8	13.8	17.0	18.5	159.1	-
2030 ERZ SAC 2km	120.8	16.4	17.9	22.1	177.6	18.5
2030 ERZ SSSI 1km	123.2	15.6	18.2	22.2	179.5	20.4
2030 ERZ SSSI 2km	137.5	17.3	19.7	26.1	201.1	42.0
2030 ERZ SSSI 5km	171.5	19.9	23.4	37.6	252.9	93.8
2030 High Amb. exc. cattle	187.9	20.3	25.9	48.2	282.4	123.3
2030 EDZ SSSI 1km	112.1	14.2	17.5	19.0	162.8	3.7
2040+ ERZ SSSI 2km inc. cattle	157.0	23.2	21.7	29.9	231.8	72.7
2040+ High Amb. inc. cattle	238.9	31.2	32.5	63.2	365.8	206.7
2030 CLe opt. ERZ SSSI‡	172.6	20.7	22.2	37.9	253.4	94.3
2030 CL opt. ERZ SSSI‡	170.4	20.8	22.8	37.7	251.6	92.5

‡ Includes emission displacement of FYM and slurries and measures to replace the use of urea fertilisers

Table 3-15 provides an overall summary of the UK findings. 2030 EDZ SSSI 1km is the most cost-effective scenario at reducing NH_3 critical level exceedance, across both the 1 and 3 µg m^{-3} CLe, and across all three indicators (DWI, AWI-1, AWI-2). This is largely due to this scenario being relatively inexpensive, in comparison to ERZ-based scenarios. In terms of the largest proportion of sites protected, the two optimised spatially targeted scenarios are the second most cost-effective options overall, but at a much greater cost than the EDZ scenario. They stand out from the other spatially targeted scenario across both the 1 and 3 µg CLe and all indicators. The optimised scenarios are, however, no more expensive than the 5 km ERZ around all SSSI, with savings from the minimum necessary variable ERZ size balancing out the estimated cost of the EDZ measures. A full assessment of cost effectiveness of measures compared to the 2030 NAPCP+DA baseline is given in Section 8 of **Annex 4**, including details at the country level.

In terms of critical loads, the implementation of EDZ is estimated to be the most-cost effective measure in terms of the number of sites brought out of CL exceedance and the cost to lower excess N. However, this is simply a reflection of the overall cost of the EDZ scenario. The results show that the high ambition scenarios provide substantial reductions in excess N deposition and bring additional sites out of exceedance. The optimised emission scenarios achieved the highest decreases in the number of sites in exceedance of CLs. In terms of effectiveness, they are the second most cost-effective measures for reducing CL exceedance. This is largely attributed to replacing the use of urea at no additional cost, which is likely to provide a significant contribution to effectiveness of the optimised scenarios.

Table 3-15. Assessment of effectiveness and cost-effectiveness of UK-wide and spatially targeted mitigation scenarios for NH_3 1 µg m^{-3} critical levels exceedance (in terms of AWI-2) and critical loads (evaluated in terms of Accumulated Exceedance, AE or excess N) for UK nitrogen sensitive SSSIs. All comparisons are made to the 2030 NAPCP+DA (NECR NOx) baseline, where 480,060 ha within SSSIs are estimated to exceed the CLe (AWI-2) and 4,485 tonnes of excess N (AAE) are estimated to be deposited.

		Critical Level Assessment			Critical Loads Assessment		
Scenario	Difference in cost (£m)	AWI-2 addit. area protected (ha)	AWI-2 % addit. area protected	AWI-2 % addit. area protected/ £5M	Reduction in AAE (tonnes N)	% reduction in AAE	% reduction in AAE/£5M
2030 ERZ SAC 2km	18.1	9,497	2.0	0.5	217	1.5	0.4
2030 ERZ SSSI 1km	20.2	9,360	1.9	0.5	228	1.6	0.4
2030 ERZ SSSI 2km	41.5	16,147	3.4	0.4	354	2.4	0.3
2030 ERZ SSSI 5km	93.3	31,562	6.6	0.4	607	4.2	0.2
2030 High Amb. exc. cattle	123.3	42,829	8.9	0.4	741	5.1	0.2
2030 EDZ SSSI 1km	3.7	23,043	4.8	6.4	455	3.1	4.2
2040+ ERZ SSSI 2km inc. cattle	72.7	20,872	4.3	0.3	792	5.5	0.4
2040+ High Amb. inc. cattle	206.7	61,189	12.7	0.3	1345	9.3	0.2
2030 CLe opt. ERZ SSSI	94.3	97,688	20.3	1.1	1524	10.5	0.6
2030 CL opt. ERZ SSSI	92.6	96,655	20.1	1.1	1519	10.5	0.6

3.4.3 Co-benefits and trade-offs with other policy areas

The mitigation strategies aimed at decreasing the impact of atmospheric N emissions on sensitive habitats and species, as tested in this project, are expected to have the following number of co-benefits with other policy areas:

Co-benefits

- Cleaner air - Human health indicators are expected to improve with all scenarios, both from NO_x and NH_3 emission reductions as sources of primary and secondary pollutants. NH_3 reacts in the atmosphere with nitric acid to form ammonium nitrate and with sulphuric acid to form ammonium sulphate particulate which are major contributions to total $PM_{2.5}$ concentrations. Additionally, air scrubbers fitted to poultry housing also provide direct reduction in PM emissions.
- Odour reduction - Some measures, such as slurry store covers and low emission application methods, which reduce NH_3 emissions by reducing the exposed manure surface area, will also greatly reduce odour emissions associated with manure management. Complaints regarding odours can influence farmer-neighbouring resident relationships and potentially impact on the farmer’s ability to operate.
- Nitrogen use efficiency - By reducing N losses either throughout the manure management chain or directly from the application of fertilisers of manures, there is a

greater potential for improved nitrogen use efficiency (NUE) within the whole farm system. This requires appropriate management of N, e.g. application to grassland/crops at the appropriate time and rate, which will result in an overall reduction in the N input to crops/grassland. For most farms this would translate into less requirement to purchase fertilisers and therefore a cost saving.
- Low emission slurry application methods i.e. trailing hose, trailing shoe and shallow injection, are associated with a much more even distribution of the slurry across the spread width than is possible with conventional surface broadcast application. This enables farmers to have better confidence in the nutrient use efficiency of the applied slurry as part of a precision integrated nutrient management system for the farm.
- Low emission slurry application methods are also associated with much less direct contamination of the crop or grassland to which the slurry is being applied, reducing issues such as leaf scorch, silage contamination and grazing refusal.
- Carbon sequestration - Additional tree planting increases carbon sequestration.
- Animal health - Lower NH_3 concentrations in livestock housing and cleaner/drier floor surfaces will have direct benefits for animal health.
- Renewable energy production - Slurry store covers may be combined with methane capture and utilisation systems, thereby reducing direct methane emissions and potentially yielding energy for use by the farm.

Trade-offs

- By reducing N losses as NH_3 volatilisation from livestock manures and urea fertiliser through mitigation measures, there is a greater readily available quantity of N being applied to soils. Ideally this additional N retained in the mineral and organic fertilisers is reflected in better N uptake by the crop, with fewer losses to the environment, as discussed above under co-benefits. However, the higher retained N content does also increase the potential for subsequent N losses by other pathways, including denitrification (with associated N_2O and NO_x emissions), leaching and direct run-off to water bodies. This potential for greater losses can be minimised by decreasing the overall organic or mineral N application rate in line with the reduction in NH_3 losses and by applying at the most appropriate time and rate according to crop requirement.
- Loss of income for land managers due to costs of measures or reduced yield/de-intensification as part of spatial targeting of measures – these issues are already being considered in existing schemes and currently being developed for future environmental land management/land use schemes.

4 Notes on interpretation

The following points cover caveats, information gaps and their implications on how the model output from this project can be used for assessing impacts of atmospheric N input to sensitive habitats and designated sites:

- Relatively detailed spatial data on location of livestock types and crops are available for UK-scale modelling (i.e. at a 1-5 km grid resolution). However, emission calculations require not only activity data in terms of livestock populations and crop areas but are very dependent on the management practices used on any given farm. Farm management practice data are not well resolved spatially and often only available at a DA-level. By contrast, in the Netherlands details on individual livestock houses and implemented measures are available for the national emission inventory estimates. There are likely to be greater spatial differences in emissions than those represented in the scenario modelling results. These may be due to the spatial implementation of specific management and mitigation practices, such as housing type, slurry or solid manure systems in use, type of slurry store, manure spreading equipment in use, *etc*. Therefore, all model outputs presented in this report are based on average condition by each country. Any subsequent use of emission maps based on these average conditions for estimating atmospheric concentrations of NH_3 and N deposition, as well as subsequent assessment of CLe/CL exceedance therefore needs to consider the potential for over- or underestimates locally. This must be considered in combination with the much finer scale local gradients and local enhancement of emission sources at a sub-1 km grid and very close to sensitive habitats or designated sites.

- Temporal variability of emissions and atmospheric N input to sensitive habitats and designated sites - Emission estimates for national inventory and scenario modelling purposes generally make use of annual emission factors. Temporally resolved emission estimates would improve the subsequent modelling of atmospheric dispersion and deposition and hence, impacts.

- Weather-dependent variability of emissions – The volatilisation of NH_3 from a surface (e.g. slurry lagoon, field) is dependent on wind speed and highly sensitive to temperature and influenced by humidity. This is not represented in any national emission inventories, as they are required to represent average conditions, to make annual emission inventory data measurable against targets (e.g. NECR ceilings). Inter- and intra-annual variability of emissions and effects is dependent on local conditions, with higher volatilisation rates in warmer periods.

- SO_2 emissions are forecast to continue to decrease. This has a controlling influence on the rate of conversion of ammonia to ammonium sulphate particulate matter. Decreased SO_2 emissions can lead to enhanced local NH_3 concentrations due to slower atmospheric chemical transformation rates.

- NO_x mitigation was not the focus of this project. Future measures were defined relatively loosely, as a proportional decrease in emissions across all sectors, rather than with a bottom-up definition of individual measures. Such measures could include faster fleet turn-over and/or electrification for road transport, fuel switching away from solid fuels and electrification for industry, switching from gas boilers to renewable energy for residential combustion. For road transport related NO_x (and NH_3) emissions, which are most relevant for areas close to busy roads, local assessment is much more appropriate for designated sites where this sector is a key source of atmospheric N input.

- Designated side boundary datasets (2011 vs 2019 versions) - Under this project an updated dataset of designated sites (2019) was prepared and used for implementing the spatially targeted mitigation scenarios. Compared with the 2011 dataset currently used as part of the NFC Trends reports, this new dataset contains additional SSSIs and SACs and uses updated site boundaries with some sites having increased in size, merged with neighbouring sites or newly designated sites. While the new boundary dataset could be used for the modelling of emissions, concentrations, deposition and critical levels exceedance, it was not possible to use it for assessing critical loads exceedance as any changes to designated features for modified sites and newly designated features for new sites have not yet been incorporated into the national NFC database. This work has started but is complex and requires further detailed communications with the relevant nature conservation agencies across the UK to be finalised, and this was not possible within the time frame of this project. Therefore, any site-based critical loads statistics in this section refer to the 2011 site database used by the NFC.

- Likely progress towards the UK Government's CAS target to "*reduce damaging deposition of reactive forms of nitrogen by 17% over England's protected priority sensitive habitats by 2030"* was assessed from data produced in the modelling undertaken in this project. Although the habitat areas included in this calculation are likely to change (due to the protected habitat datasets still being under development by the Statutory Nature Conservation Bodies), this is unlikely to greatly affect relative change in deposition onto the total area. Apart from the 2030 BAU (WM) scenario, which does not meet NECR objectives either, all scenarios are estimated to meet the target.

- The UK Government's CAS deposition target for 2030 is clear and simple but does not consider the differences in the sensitivity of habitats, e.g. as expressed in terms of empirical critical load. Metrics such as *Excess N* and *Percentage Area Exceeded* provide a more accurate picture of changes in the pressure on habitats and protected sites from N and acidity pollution.

- Ecosystem condition metrics (e.g. species richness, species composition) were not calculated for the scenarios due to time constraints. Statistical and dynamic models are available that could be used to calculate likely effects on many aspects of ecosystem condition. This would introduce more uncertainty, but such metrics can be related more directly to biodiversity endpoints and to site records of habitat condition.

5 Recommendations for further research

Spatial targeting of measures for designated sites sensitive to and affected by atmospheric N can be taken forward to the pilot stage without further research, in principle – i.e. local assessment established through measurements of atmospheric N inputs, screening of local sources, agricultural practice/systems/measures in place, establishing a measurement baseline before new measures are targeted, and – last but not least - local stakeholder engagement initiated. Some aspects of this have already been initiated: In total, 12 SACs were originally proposed for SNAP pilots and over half of these have been actively progressed, and are at various stages of planning, information gathering and external stakeholder engagement. The majority of SNAPs with sufficient resourcing are in the process of characterising the site, identifying local emission sources and emissions contributing to critical load exceedance. The most progressed SNAPs have now identified and held workshops with external stakeholders to scope objectives and share expertise.

The following suggested further work would be helpful for

- developing the evidence base for assessments of environmental effects from atmospheric N at sites (either rolled out nationally, or for local priority implementation);
- ongoing assessment of new (or new to the UK) mitigation measures, for relevant pollutants across all sectors;
- systematic updating of relevant and accessible digital datasets across the UK's countries (source attribution, databases of sensitive habitats and designated sites, including location of designated features within sites);
- development and application of dynamic models and additional metrics and indicators;
- baseline research to quantify exposure pathways, pollutant mixes, orographic enhancement, the latter for improving N deposition estimates for the upland areas; and
- further scenario modelling to investigate what could theoretically be achieved with much more ambitious mitigation strategies for stretch targets in further decreasing atmospheric N input to sensitive systems.

Environmental effects research and metrics

- Predicted species composition is a quantitative representation of a habitat. Further work is needed to link this quantification to biodiversity targets, e.g. for habitat condition. Policy-stakeholder decision making is needed to clarify which habitat classification system(s) should be considered, and to develop quantified targets for each habitat included e.g. in terms of indicator species.
- The interacting effects on habitats of different N exposure pathways (e.g. mineral N in soil, gaseous NH_3 and NO_x), and exposure to other pollutants, are not well characterised. It would be useful to review and discuss the evidence on relative effects and interactions, and whether these are reflected in the ways Critical Loads and Critical Levels are currently applied.
- Further development and application of dynamic models of soil and species change in response to pollution would be useful to account better for chemical delays and delays in species responses. Interactions with changes in management, climate, *etc*. can be allowed for in such models and target loads developed to predict the likely recovery timescale after the critical load has been exceeded for some time.
- Additional work to clarify the knock-on effects of N on other ecological functions and ecosystem services would be useful, to help illustrate the wider impacts on society beyond those just on biodiversity.

Assessment of cost-effective mitigation methods

Continued/further methods development would be welcome for improving information that can be used for similar assessments in the future including advances in animal and crop nitrogen use efficiency (NUE) under current and novel systems. This should include reviewing systems being developed in other countries (e.g. various dairy housing designs in the Netherlands) to assess their applicability (and cost) for implementation in the UK.

Updated source attribution dataset
The source attribution dataset currently available is based on data for the year 2012 which is now considerably out of date. The dataset should be updated to 2017 which is the most recent year of spatial data available from the UK NAEI. It is further recommended that deposition to the UK originating from emissions on the wider European continent (i.e. the transboundary input) should be split into deposition originating from the Republic of Ireland vs. mainland Europe. This is of particular interest for Northern Ireland which shares a land border with the Republic of Ireland so that cross-border deposition can be quantified, and mutual mitigation strategies developed.

Additional scenario exploration
It may be of interest to consider exploring additional scenarios for more stretching targets. This could include testing more ambitious measures for agricultural ammonia (the main focus of this project), or including other alternative future outcomes, rather than “business-as-usual” projections, such as changes to human diet, or transport, in light of recent insights from the COVID-19 disruption of “normal” life, business, transport, *etc*. From an agriculture perspective. further emission reductions might be achieved with more widespread implementation of various types of low emission livestock housing (but at high cost), agricultural N use efficiency improvements through the development and adoption of crops and livestock of improved genetic merit (enabling same output for lower input). Other options that could be explored could include structural changes to the agricultural sector such as significant reductions in cattle and sheep numbers associated with direct or indirect policies aimed at changing human diet (move away from red meat and dairy), or significant changes in land use and associated displacement of emission activities.

Investigation into potential changes to current and future emissions due to COVID-19
Improvements are being made to the emission projections for the UK and the Devolved Administrations depending on the availability of improved information on future trends and because the historical data that the projections are based on are revised on an annual basis. Similarly, the spatial distributions of e.g. population, traffic counts, *etc*. that are used to generate the national emissions maps from the national emissions inventory are periodically updated. In much the same way that emission projections are periodically updated, the quantification of the impact of policies and measures is also improved. It is therefore sensible to monitor the extent to which emission projections (under different scenarios) and the emission maps are recalculated, and to evaluate whether this has the potential to substantially impact on the findings of this project. This is particularly the case for the impacts of the coronavirus pandemic (COVID-19). At the time of writing, it is not possible to reliably assess the speed with which economic activities will return to pre-virus levels. However, it is possible to note that the impact on current and future NO_x emissions due to behavioural change is likely to be substantial, and by comparison the impact on NH_3 emissions is expected be much smaller.

6 Conclusions

The Nitrogen Futures project updated and further developed the UK evidence base for informing policy development on:

- the effectiveness of spatially targeting mitigation for atmospheric nitrogen emissions of NH_3 and NO_x;
- environmental outcomes of meeting 2030 NECR targets and impact of modelled mitigation scenarios on the CAS “17% target”;
- future agri-environment schemes, in particular goals regarding “spatial targeting” and “landscape scale land use change” as outlined in a current consultation for England; and
- outcomes of potential regulatory action for large cattle farms, as stated in the CAS.

This was achieved through high resolution modelling with substantially updated modelling tools at a 1 km grid resolution, with a new base year (2017, previously 2008 in Defra project *AC0109 Ammonia Future Patterns*), for the new NECR target year (2030, previously 2020). The scenario development incorporated the latest UK and DA government thinking on ammonia and NO_x mitigation through consultation with the project steering group and included recently developed metrics.

The UK-scale modelling and local scale assessment carried out focused on quantifying expected baseline conditions for 2030 and the potential for further more ambitious UK-wide and spatially targeted sets of measures for 2030 and beyond (2040+), and predict their likely impact on atmospheric N input to sensitive habitats and designated sites.

The scenario modelling predicts a substantial decrease in risk of impacts on sensitive vegetation by 2030, under the most likely future baseline. This assumes that NECR targets will be met through implementation of the UK National Air Pollution Control Programme (NAPCP), with modifications to suit the Devolved Administrations. This is estimated to achieve the UK Government’s CAS target for England, defined as a 17% decrease in total reactive N deposition onto protected priority sensitive habitats, with a predicted 18.9% decrease from a 2016 base year. All other scenarios achieve the target, thereby enabling progress towards the targets of the UK Government’s 25 Year Environment Plan.

The results illustrate that targeting zones surrounding designated sites is the most efficient and cost-effective solution for implementing mitigation measures to benefit the sites, per unit of emission reduction. At an individual site level, targeting measures within buffer zones can be almost as effective as applying measures UK/country-wide, in terms of reducing atmospheric N input to the site, although clearly wider measures are more beneficial for sensitive habitats beyond protected sites. The characteristics of the site and the principal emission sources contributing to atmospheric N input are key for predicting whether spatial targeting is effective. Designated sites that are subject to high levels of local atmospheric N input, from either farming activities or road transport, could be effectively targeted with locally implemented measures. By contrast, for sites remote from local emission sources, the main drivers for improvement are wide-ranging national and international mitigation efforts, such as those to meet the current NECR/NECD targets.

The effectiveness of the modelled spatial targeting measures varies across the UK, the four countries and between sites - this is due to the make-up and density of the emission source sectors near each site, and the ability to influence concentrations or deposition through the bundle of measures tested. For example, most sites in the Scottish Highlands and Islands are exposed to very little atmospheric N input from local sources. This means that decreasing deposition onto these sites depends on ambitious mitigation elsewhere in the UK. In Northern Ireland, high emission densities from agriculture mean that much of the atmospheric N input originates within the country. Therefore, both ambitious country-/UK-wide measures and local targeting are required to decrease the current very high levels of exceedance of critical loads and levels. This modelled decrease of atmospheric N inputs through mitigation scenarios would not only result in fewer designated sites exceeding their critical loads or levels, but also achieve a decrease in excess N above these thresholds for sites still in exceedance, thereby reducing the severity of negative effects and bringing habitats closer to the thresholds.

Overall, the more ambitious scenarios had the most impact, with the largest numbers of designated sites and priority sensitive habitats coming out of exceedance or substantially decreased excess atmospheric N input. In particular, the optimised scenarios, which combined Emission Reduction Zones (ERZ) and Emission Displacement Zones (EDZ) around designated sites with phasing out of urea-based fertiliser, stood out as the most cost-effective option, for much of the UK. However, the scenario analysis also showed that there is no single “one size fits all” solution that will be the most effective approach across all parts of the UK. For example, the widths of the ERZ clearly depend on the local emission densities surrounding each site, with some sites requiring no intervention, whereas for others, in areas of very high N emissions and concentrations, even a 5 km zone may not be sufficient to decrease atmospheric N input sufficiently. Instead, the concepts of ERZ and EDZ could be implemented as part of a framework, with suitable measures and zones tailored for ambition levels and local sources. Nested within and combined with UK (or country)-wide efforts, spatially, such as those planned under the NAPCP, targeted measures are expected to provide environmental benefits across large numbers of designated sites.

In summary, the following approach for maximising the effectiveness of mitigation measures for the benefit of designated sites is proposed:

- Implementation of UK/country-wide measures to decrease NH_3 and NO_x concentrations and N deposition – Measures include emission reduction across all source sectors, e.g. agriculture, waste processing, transport and other combustion sources. This will lead to improved conditions for sensitive habitats and species in both source areas as well as in remote areas where long-range deposition will be reduced. For remote sites and wider sensitive priority habitats that are not located within designated sites this will be the only strategy to decrease atmospheric N input.
- Spatial targeting - the implementation of local targeted mitigation measures is more effective at “spot-reducing” high concentrations and dry deposition than the same amount of emission reduction implemented widely across the UK. This is the most effective strategy to decrease impacts of N in designated sites subject to high levels of local N input. It should be combined with measures to decrease wider regional background concentrations and related local dry deposition. Effective spatial targeting of measures needs to consider local emission source types, management practices and systems in place and related opportunities for improvement. This requires local engagement with all stakeholders, for example through the implementation of Natural England’s Shared Nitrogen Action Plans (SNAP) or similar approaches.
- A mix of well understood and effective measures applied more widely as well as specific spatially targeted measures - the tested examples of Emission Reduction Zones (ERZ) and Emission Displacement Zones (EDZ), embedded in a UK-wide mitigation programme, do not need to be applied as nationally prescriptive sets of measures but can rather be used as frameworks for locally suitable measures.

7 Acknowledgements and Evidence Quality Assessment

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- Joint Nature Conservation Committee
- Department for Environment, Food & Rural Affairs (England)
- Department of Agriculture, Environment and Rural Affairs (NI)
- Scottish Government
- Welsh Government
- Scottish Environment Protection Agency
- Natural England
- Natural Resources Wales

The Nitrogen Futures quality assessment process had a 3-tiered approach:

Tier 1 – Review by the scientific project team
Quality assessment was implemented by the scientific team members in accordance with their affiliated organisation quality assessment policies. The project manager (JNCC) and Air Pollution scientific adviser (JNCC) also reviewed the final report and annexes at this stage.

Tier 2 – Review by the Steering Group
After the review process in Tier 1, report and annexes were reviewed by the Steering Group members for final review and sign-off.

Tier 3 – Review by the Quality Assessment Board
During the project governance set up phase, a technical group to be consulted at different stages of the project was created. Three members of the technical group were identified to review the final report before final sign-off by JNCC Chief-Scientist and publication online.

8 Glossary

Acronym	Meaning
AAE	Annual Average Exceedance
ASSI	Area of Special Scientific Interest (Northern Ireland), equivalent of SSSI in Great Britain
AENEID	Atmospheric Emissions for National Environmental Impacts Determination. A model to produce high-resolution (1 km grid) maps of agricultural ammonia, methane and nitrous oxide emissions for the UK, annual maps available through the NAEI
BAU	Business As Usual - includes only those policies that have already been adopted or implemented at the time of the project projection compilation. It does not include additional measures set out in the NAPCP which are designed to meet NECD/NECR targets.
CBED	Concentration-Based Estimated Deposition, a model generating maps of deposition of sulphur, oxidised and reduced nitrogen
CCE	Coordination Centre for Effects, of the WGE
CNCBs	Country Nature Conservation Bodies (Natural England, Scottish Natural Heritage, Natural Resources Wales, Council for Nature Conservation and the Countryside)
CL	Critical Load, an amount of deposition per unit area and time. The formal definition is “a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge” (Nilsson & Grennfelt 1988)
CLe	Critical Level, a concentration in air e.g. of ammonia, below which harmful effects do not occur according to present knowledge
CL_{empN}	Empirical critical load for nutrient-nitrogen, as defined in Bobbink *et al*. (2011) and refined for the UK by Hall *et al*. (2011)
CLRTAP	Convention on Long Range Transboundary Air Pollution
DA	Devolved Administration
Daera	Department of Agriculture, Environment and Rural Affairs
Defra	Department for Environment, Food & Rural Affairs
ECA	Emission Control Area
EDZ	Emission Displacement Zone
ELM	Environmental Land Management
ERC	Emission Reduction Commitments
ERZ	Emission Reduction Zone
EU	European Union
FAPRI	Food and Agricultural Policy Research Institute
FRAME	Fine Resolution Atmospheric Multi-pollutant Exchange (atmospheric chemistry and transport model)
ha	Hectares. One hectare is 100 m x 100 m
ICP-M&M	International Cooperative Programme for Modelling and Mapping critical loads and critical levels.
IED	Industrial Emissions Directive
LEZ	Low Emission Zone (a defined area where access by some polluting vehicles is restricted with the aim of improving air quality)
MCPD	Medium Combustion Plant Directive
N	Nitrogen. Strictly, reactive N, i.e. including oxidised and reduced forms of N but not dinitrogen gas, N_2.
NAEI	UK National Atmospheric Emissions Inventory
NAMN	UK National Ammonia Monitoring Network
NARSES	UK agricultural emission model (spreadsheet based), developed by Rothamsted Research
NAPCP	National Air Pollution Control Programme
NE	Natural England
NECD	EU Directive on the Reduction of National Emissions (2016/2284)
NECR	UK National Emission Ceilings Regulations (2018 No 129) transposing NEC Directive 2016/2284/EU.
NFC	UK National Focal Centre, under ICP-M&M

NFR	Nomenclature for Reporting (Format for reporting of national emission data in accordance with the CLRTAP)
NH_3	Ammonia
NMVOC/VOC	Non-Methane Volatile Organic Compounds/Volatile Organic Compounds
NO_x	Nitrogen Oxides
NRMM	Non-Road Mobile Machinery
NRW	Natural Resources Wales
MCPD	Medium Combustion Plant Directive
PaMs	Policies and Measures
PCM	Pollution Climate Mapping (model)
PM	Particulate Matter
SAC	Special Area of Conservation, designated site protected under the Habitats Directive
SEPA	Scottish Environment Protection Agency
SNAP	Shared Nitrogen Action Plan
SNAP (sectors)	Selected Nomenclature for reporting of Air Pollutants. Pollution sources categorised into sectors for reporting. For example: S3 – Combustion in manufacturing industry, S7 – Road Transport, or S10 Agriculture.
SNCBs	Statutory Nature Conservation Bodies (Joint Nature Conservation Committee, Natural England, Scottish Natural Heritage, Natural Resources Wales, Northern Ireland Natural Environment Division)
SNH	Scottish Natural Heritage
SO_2	Sulphur Dioxide
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
UAN	Urea Ammonium Nitrate (a liquid fertiliser combining urea, nitric acid, and ammonium)
WAM	With Additional Measures. This scenario includes policies that have been adopted and implemented as well as those that are planned.
WGE	Working Group on Effects, within CLRTAP
WM	With Measures. This scenario includes policies that have been adopted and potentially implemented at the time of projection compilation.
WP	Work Package

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10 Annexes

The annexes described below are part of this main report and are available at: https://jncc.gov.uk/our-work/nitrogen-futures/#project-outputs

Annex 1: Future nitrogen emission scenarios & comparison with baselines.
Detailed information on projections of activity data and emission factors, methodology.

Annex 2: Development of spatially targeted scenario options for 2030 and beyond
Review of options for scenario modelling and selection of a subset for implementation under UK scale scenario modelling and local demonstration.

Annex 3: Ecosystem benefit metrics
Review of ecosystem benefit metrics and selection of sub-set to be used for UK scale scenario modelling and local demonstration; recommendations for future development of metrics.

Annex 4: UK scenario modelling and policy evaluation
Outputs from UK scale scenario modelling (1 km grid resolution), including tables, graphics and datasets, at UK and country level, provides more detailed analysis than the main report.

Annex 5: Local demonstration
Local case studies for local assessment of spatial targeting of mitigation, including methods and outputs.

Annex 6: Extended scenario description table
Excel spreadsheet providing more details for the 15 scenarios modelled in a single larger summary table.