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Accounting for the uncertainty in nitrogen deposition estimates in support of policy

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ABSTRACT

Deposition of reactive nitrogen (N_r) onto sensitive habitats in exceedance of Critical Load (CL) thresholds can drive biodiversity loss and affect ecosystem function. N_r deposition is a highly complex process that is difficult to measure and model, leading to large uncertainties.

We assess the implications for policy development and target setting of the large range in estimates provided by different modelling approaches.

We considered three UK models (UKIAM, EMEP4UK, CBED), used to inform national policy and responses to the UN-ECE Air Convention. We used a scaling method to project the range in current estimates to future scenarios, and a risk-based approach to provide a probabilistic assessment of exceedances. We considered two future scenarios, a 2040 baseline and a 2040 high ambition technological measures scenario, in relation to a 2018 baseline.

The 2018 baseline CL exceedances are highly dependent on the model used – Average Accumulated Exceedance of 1.3–9.1 kg.N.ha^{-1}.yr^{-1} across all habitats. The relative reduction in exceedances for future scenarios also depends on the model, with a range of 30–66 % achieved by 2040 for the high ambition scenario, posing a challenge for target setting. Despite this, it's clear that a much greater level of ambition is required to protect the majority of habitat areas. Our risk-based approach shows that implementing only technological measures is likely to leave most areas in exceedance in 2040.

This uncertainty in the assessment of N_r deposition and the benefits of abatement measures poses a challenge for policy development that is not unique to the UK.

1. Introduction

The deposition of reactive nitrogen (N_r) in its various forms (e.g. NO_3^-, NH_4^+, NH_3, HNO_3, NO_x) on nitrogen-sensitive habitats is a major driver of global biodiversity loss (e.g. Stevens et al., 2011; Bobbink et al., 2010; van der Plas et al., 2024). High rates of N_r deposition lead to the eutrophication of soils and freshwaters, resulting in the loss of species that are outcompeted when N_r availability is increased. High N_r deposition rates also potentially lead to acidification, causing nutrient deficiencies and reduced plant productivity, and the loss of acid-sensitive species. These impacts on sensitive habitats can induce changes in the flora (e.g. Dise et al., 2011; Stevens et al., 2016) and fauna (Nijssen et al., 2017) associated with these habitats and habitat function, which in turn can affect ecosystem services provided by the habitat. Atmospheric N_r deposition can have positive and negative impacts on the ability of an ecosystem to sequester carbon from the atmosphere (e.g. Bragazza et al., 2006; de Vries et al., 2009; Laudon et al., 2024) which may have implications for Net Zero targets.

Critical Loads (CLs) are estimates of the annual deposition rate below which a habitat is not considered to be significantly harmed (Nilsson and Grennfelt, 1988). Vast areas of nitrogen sensitive habitat are estimated to be in exceedance of their CLs in many developed countries such as the United States (Clark et al., 2018) and most European Union countries (European Commission, 2022a). In the UK, the vast majority of all nitrogen sensitive habitat areas are estimated to be in exceedance of their CLs (Rowe et al., 2024).

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The biggest source of deposited atmospheric N_r in the UK is NH_3 from agriculture (Woodward et al., 2022), followed by NO_x emissions from road transport, the power sector and shipping. Emissions of NO_x are projected to decrease considerably with electrification of road transport and power sectors (e.g. Mehlig et al., 2021). Future emissions from shipping are more uncertain. Ammonia has been proposed as a low-carbon replacement for fossil fuels (e.g. UK Net Zero Strategy BEIS (2021)), which is likely to result in sustained NO_x emissions, combined with additional fugitive NH_3 emissions. Agricultural NH_3 has proven to be particularly difficult to abate, with the majority of agricultural NH_3 emissions associated with livestock production (Defra, 2024). Despite some efforts to reduce these emissions through technological solutions (e.g. low emission spreading of fertiliser and improved manure management; Defra, 2018), total NH_3 emissions have remained fairly steady in the UK since 2010 (Defra, 2024). Since 2010, some success in abatement, coupled with a gradual reduction in cattle numbers, has been countered by increasing emissions in certain sectors such as non-manure digestate (increasing from 1.6 kt NH_3 in 2005 to 13.1 kt NH_3 in 2021 (Carswell et al., 2024)). Other countries have demonstrated that significant reductions in total agriculture NH_3 are possible using technological measures, for example the Netherlands saw a reduction in total NH_3 of 64 % between 1990 and 2014 (Wichink Kruit et al., 2017). Unless total NH_3 emissions in the UK are reduced substantially, CL exceedances are likely to remain high (Woodward et al., 2022).

Large uncertainties are associated with both measured and modelled values (Dore et al., 2015; Cowan et al., 2022; Williams et al., 2017; Walker et al., 2019)). We discuss the underlying reasons for these uncertainties in Section 4. The uncertainty in deposition estimates is reflected in the range given by different models that have been applied to the UK (RoTAP, 2012; Dore et al., 2015; Woodward et al., 2022). Here we used three models to illustrate the significance of this range in estimates on the assessment of CL exceedances in the UK. There is also uncertainty in the CL values assigned to N-sensitive habitats (e.g. Bobbink and Hettelingh, 2011; Bobbink et al., 2022). For N_r deposition, a range in CL is determined for each habitat following review of empirical evidence by an expert group, with the exception of managed coniferous woodland for which CL is set using a mass balance approach. The range assigned to each habitat represent both the uncertainty in the derivation of the CL and the ecosystem response, but also the variation in sensitivity within a habitat. When evaluating CL exceedances at national level without a local assessment of a habitat area, the variation within a given habitat contributes to the uncertainty in the assessment. While these CLs have proven useful as a measure of the varying degrees of resilience of different habitats to excess N_r, and to inform international negotiations under the Convention on Long-Range Transboundary Air Pollution (CLRTAP), they are an additional source of uncertainty in the assessment of N_r deposition impacts (Jones et al., 2016).

These uncertainties pose a challenge to the use of modelled N_r deposition and CL exceedances in support of policy. Here we used the risk-based approach described in Woodward et al. (2022) to illustrate the significance of uncertainty in N_r deposition estimates when assessing impacts on sensitive habitats at a national scale. Policymakers often require projections of the degree of improvement achieved by a future date as a result of proposed interventions, to inform their decisions. We therefore assessed the difference between models in the predicted decrease in deposition and exceedances relative to the 2018 baseline year.

We considered the implications of the range in forecast deposition for policy development aimed at reducing the harmful impacts of N_r deposition, such as the target to reduce N_r deposition onto sensitive habitats in England by 17 %, set in the UK Clean Air Strategy (Defra, 2019), i.e. all areas of priority habitat including those not within protected sites (Rowe et al., 2024). Implications for broader habitat restoration targets were also considered both in the UK, in the European Union and consideration for the Gothenburg Protocol revision.

2. Method

Three models are used for our analysis, each of which are each used in support of UK policy development. The Concentration Based Estimated Deposition (CBED) (APIS,) is a semi-empirical inferential model used for CL exceedance reporting in the UK (Rowe et al., 2024) and for UK reporting under CLTRAP. The UK Integrated Assessment Model (UKIAM) is used in support of UK air policy development and was a key tool providing evidence in support of the targets set in England's Environment Act 2021; ApSimon et al. (2022). The EMEP4UK model (Ge et al., 2021; Gu et al., 2021; Skamarock et al., 2019; Vieno et al., 2016a, b) is also a key model used in support of these targets and is a UK high resolution implementation of the European EMEP MSC-W model (Simpson et al., 2012). The European EMEP model is used extensively in support of policy development under the CLRTAP.

The CBED model is calibrated using measurement data and therefore a meaningful validation challenging. The validation of CBED in the literature is limited to the validation of the models used to interpolate between measurement points, such as the seeder-feeder model. Even in this case, validation is limited (e.g. Beswick et al., 2003; Dore et al., 2006).

Dore et al. (2015) performed a model intercomparison a "fitness for purpose" analysis which includes EMEP4UK and FRAME. FRAME is a Lagrangian ACTM which underpins UKIAM. Both models are deemed fit for purpose based on the criteria used by Dore et al. (2015). Despite this, the paper also highlights clear differences between these two models, with EMEP4UK typically giving lower estimates of concentrations and concentrations in precipitation than FRAME. A statistical comparison of UKIAM and CBED is given in Woodward et al. (2022). The EMEP MSC-W model is routinely and extensively compared with observations across Europe, including the UK (MSC-W & CCC, 2020), and Ge et al. (2021) undertook a global study demonstrating acceptable performance.

2.1. The UK Integrated Assessment Model

The UKIAM models atmospheric concentrations and human population exposure to harmful air pollutants (ApSimon et al., 2021, 2023; Oxley et al., 2023), and also evaluates the impact of air pollutants on sensitive habitats (Woodward et al., 2022). The model combines UK emissions of NH_3, SO_2, NO_x and $PM_{2.5}$ with transboundary contributions from other countries and international shipping, allowing the sources of deposition to be apportioned across different sectors. UKIAM estimates deposition for future scenarios by scaling Source-Receptor (S-R) footprints of deposition, generated by an ACTM, to reflect the change in emissions relative to a base case. The Fine Resolution Atmospheric Multi-pollutant Exchange (FRAME) model (Dore et al., 2007; Vieno et al., 2010; Hallsworth et al., 2010; Aleksankina et al., 2018) was used to generate these S-R footprints using average meteorology over a number of years. FRAME includes a simple enhancement term for areas of higher altitude and precipitation which attempts to capture the additional deposition due to the seeder-feeder effect (Dore et al., 1992; Smith and Fowler, 2000) (see Discussion for explanation of seeder-feeder effect).

The scaling of S-R footprints means that a linear relationship is assumed between the change in deposition due to a change in emissions from a source. This linear assumption has been shown to be acceptable for variations in emissions of ±40 % (Aleksankina et al., 2018), i.e. within this range the effect of non-linearity is acceptable relative to other uncertainties.

Different deposition velocities are assumed for short semi-natural habitats, such as grasses and dwarf shrub heath, than for taller habitats, such as woodlands. Fertilised habitats are not considered in this study. Separate maps are generated for deposition onto short habitats, referred to as "moorland", and onto woodland. A detailed description of the UKIAM is provided by ApSimon et al. (2021) and Oxley et al. (2023).

Table 1
Nitrogen deposition habitat areas and critical loads.

Habitat	Area in the UK (km^2)	EUNIS habitat class	Habitat type for deposition	CL_{min}-CL_{max} range (kg N ha^{-1} yr^{-1})	CL_{rec} (kg N ha^{-1} yr^{-1})
Acid grassland dry & wet	20365	R372 & R1M (E1.7 & E3.52)	Short	6-10 & 10-20	6 & 10
Calcareous grassland	1012	(R1A)E1.26	Short	10–20	10
Dwarf shrub heath (wet & dry)	21846	S411 & S42 (F4.11 & F4.2)	Short	5–15	5
Montane	4915	E4.2[a]	Short	5–10	5
Bog	9118	Q1 (D1)	Short	5–10	5
Managed coniferous woodland	14450	T31 (G3)	Tall	10–15	10
Broadleaved woodland	8706	T1 (G1)	Tall	10–15	10
Beech woodland (unmanaged)	2059	T17 (G1.6)	Tall	10–15	10
Acidophilous oak woodland (unmanaged)	6958	T1B (G1.8)	Tall	10–15	10
Scots Pine woodland (unmanaged)	1485	T35 (G3.4)	Tall	5–15	5
Mixed woodland	1422	G4	Tall	10–15	10
Dune grassland	631	N15 (B1.4)	Short	5–15	5
Saltmarsh	808	MA223/MA224/MA225 (A2.53/54/55)	Short	10-20 & 20-30	10 & 20

[a] The 2023 revision of EUNIS codes does not include a class for montane habitats (formerly moss summits) hence the critical load for E4.2 has been retained.

2.2. CBED

CBED is based on measurements collected at sites in the UK Eutrophying and Acidifying Pollutants (UKEAP) network (Conolly et al., 2023). To smooth the concentration fields of secondary pollutants (e.g. NO_3^- and NH_4^+ aerosols and HNO_3 gas) CBED uses interpolated maps of the measured values. For the primary pollutants NH_3 and NO_2, concentrations are predicted with EMEP4UK and the Pollution Climate Mapping model (Defra n.d.), respectively, and scaled with the measurement data, before being combined with data on landcover and meteorology to generate a 5×5 km^2 map of deposition values across the UK. The CBED model estimates dry deposition using a “big leaf” approach (Smith et al., 2000), combining gas and particulate concentration maps, constrained to measurements, with maps of vegetation cover and average meteorology. The model accounts for vegetation-specific deposition velocities and includes a simple model of bidirectional exchange of ammonia that allows for stomatal emission.

Wet deposition is estimated by combining spatially distributed measurements of concentrations in precipitation with annual precipitation maps from the UK Meteorological Office. An enhancement term is included to account for the seeder-feeder effect (Dore et al., 1992; Smith and Fowler, 2000). A parameterisation of occult deposition is also included. CBED was designed to be independent of the uncertainty in emission inventories, and is driven by measured concentrations, so is not mass-conserved. In CBED a doubling in the deposition velocity results in a doubling in deposition. By contrast, in an ACTM, increased deposition depletes the air resulting in less deposition later on or downwind.

CBED predicts the average deposition over three years, rather than a single year.

As with UKIAM, CBED applies “moorland” deposition rates to short unfertilised vegetation and “woodland” deposition rates for taller, woodland habitats.

2.3. EMEP4UK

EMEP4UK is a full Eulerian atmospheric chemistry transport model (ACTM). EMEP4UK simulates emissions, transport, chemical transformations and deposition of a wide range of pollutants with hourly outputs (e.g. Vieno et al., 2014). The model resolves deposition rates for the UK at approximately 3×3 km^2 resolution nested within a European domain with a resolution of 27×27 km^2. The Weather Research and Forecasting (WRF) model (Skamarock et al., 2019) provides the meteorological input data. EMEP4UK uses a tiled deposition approach and for each grid cell calculates separately the deposition received by each of coniferous woodland, deciduous woodland, crops, short seminatural vegetation and water land-cover types (Simpson et al., 2012).

2.4. Habitats and critical loads

The nitrogen-sensitive habitats that were considered for analysis are shown in Table 1, along with the range of CL values assumed. CL values were based on the ranges proposed in the latest CLRTAP review (Bobbink et al., 2022). Exceedances were calculated using the lower end of the proposed CL range for each habitat, which is the value used for UK exceedance reporting (Rowe et al., 2024). These habitat areas and CLs were mapped at 1×1 km^2 resolution across the UK, with a proportion of each grid square assigned to each habitat. Exceedance of CL were calculated for each grid square where a habitat is present, using deposition calculated by each of the three atmospheric models. The habitat type specified in Table 1 determined whether the moorland (short) or woodland (tall) deposition map were used.

As a metric of exceedance across a region the Average Accumulated Exceedance (AAE) is often used:

$$AAE = \frac{1}{A_T} \sum_{h=1}^{H} \sum_{i=1}^{N} E_i \times A_i$$

Where E_i and A_i are the exceedance and area of a habitat in grid square i, respectively. H and N are the total number of habitats (13) and grid squares, respectively, and A_T is the total area of all habitats $A_T = \sum_{h=1}^{H} A_i$. The exceedance was calculated as $E_i = \max(0, D_i - CL_{reci})$ where D_i is the land cover specific deposition of N_r for grid square i, and CL_{reci} is the recommended CL.

The recommended CL lies within the range agreed upon in international workshops under CLRTAP and is chosen by UK experts to reflect UK-specific factors such as soil pH and annual precipitation. Since the latest review, CL_{rec} has been set to equal the minimum value for the CL range, CL_{min}.

Another often reported metric is the percentage of habitat area in exceedance.

2.5. Exceedance score

In recognition of the high uncertainty in deposition estimates and the uncertainty and variability in CLs, we developed a probabilistic approach for the evaluation of N_r deposition exceedances (Woodward et al., 2022). The method, which is based on the UK Nitrogen Decision Framework (NDF) (Jones et al., 2016), uses lower and upper estimates of deposition and the CL_{min} and CL_{max} values from Bobbink et al. (2022) for the CL range.

To obtain these lower and upper estimates across the UK we follow the scaling method described in Woodward et al. (2022). We first calculate a map of the ratio of CBED and EMEP4UK deposition values for the base year 2018. We use EMEP4UK here instead of UKIAM, which is used in Woodward et al. (2022), because EMEP4UK typically gives lower estimates (see Section 3.1) and therefore will provide a better estimate of the lower bound. We then use this map to scale our EMEP4UK deposition estimates for all future scenarios to produce a second set of deposition estimates, E4UK-Scaled, as follows:

$$N^i_{E4UK-Scaled} = N^i_{E4UK} \times \left(\frac{N^{2018}_{CBED}}{N^{2018}_{E4UK}}\right)^i \quad \text{for each grid square } i.$$

We then take the lower and upper deposition estimate in each grid square to derive our lower and upper maps of deposition as follows

$$N^i_{min} = min\ (N^i_{E4UK}, N^i_{E4UK-Scaled}),$$

$$N^i_{max} = max\ (N^i_{E4UK}, N^i_{E4UK-Scaled}).$$

CBED suggests higher deposition than EMEP4UK across the vast majority of grid squares in 2018 and so the map of upper estimates, N_{max}, closely resembles the E4UK-Scaled map, while N_{min} resembles EMEP4UK.

This scaling method is not mass-conservative as it artificially enhances deposition rates. In reality, higher deposition rates would mean lower pollutant concentrations in the air, or higher emissions than that assumed in the simulation. The method is not intended to replicate the complex physics of atmospheric deposition, rather it is intended as a policy tool which communicates the degree of uncertainty in deposition estimates to policymakers.

In reality there is also an uncertainty range associated with the estimates of each model and actual deposition may lie outside this range. However, they are intended to represent a proportion of range of possible deposition values and cover the range of predictions used to inform policy.

We combine this range with the range in CL estimates that are allocated to each N-sensitive habitat (Table 1). This range reflects the variation in the level at which damaging impacts can occur from one site to another (for example, because of differences in rainfall, soil pH, management, nutrient limitation) and uncertainty in the empirical data on which the critical load is set. While the NDF adjusts the range in CL values defined by the European Nature Information System (EUNIS) to reflect the confidence in their suitability for UK specific habitat areas, here we use the unadjusted ranges given in Table 1.

Fig. 1 is an illustration of how the exceedance score is derived. In the case that the full range of deposition estimates is less than the minimum critical load, then exceedance is considered to be very unlikely (P0). The probability then increases until we reach the very likely case (P5) where the entire deposition range exceeds the maximum CL.

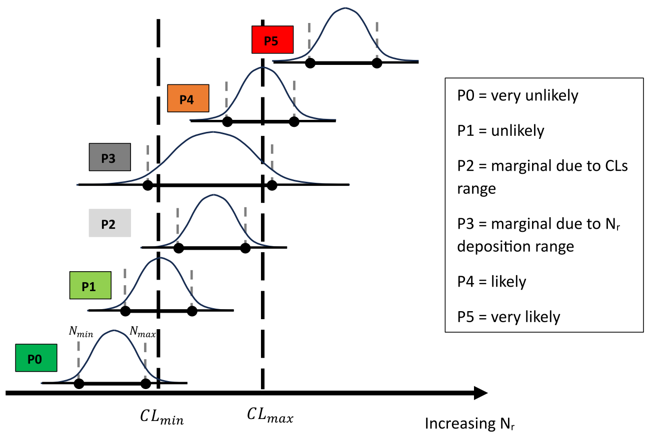

Fig. 1. Illustration of exceedance scores. The distributions represent the true uncertainty distribution. We assume that our values for N_{min} and N_{max} derived from the range in model estimates represent points near either end of the distribution. CL_{rec} is shaded because this is not used for the derivation of the score. We show it here in aid of the discussion.

2.6. Emissions scenarios

We consider three scenarios for the analyses reported here, which are consistent with the scenarios considered for a model intercomparison focussed on $PM_{2.5}$ air quality (Oxley et al., 2023):

B2018 – The baseline in 2018. The UK baseline emissions are taken from the UK's National Atmospheric Emission Inventory (NAEI) (Churchill et al., 2022; Carswell et al., 2024). Emissions of other countries reflect scenarios developed by the International Institute for Applied Systems Analysis for the EU's 2nd Clean Air Outlook, with additional measures. The EMEP4UK shipping emissions are derived from the EMEP CEIP emissions inventoried and may be different to the shipping emission uses in the UKIAM, where the emissions from shipping are modelled based on Ricardo Automatic Identification System tracking data for the domestic and international fleets around the UK. 2018 is chosen as a year as this is the base year for many air pollution targets set by the UK government in the Environment Act 2021.

B2040 – baseline 2040 emissions assuming existing interventions and policies with a natural technology turnover. This does not include the electrification of road transport and the power sector. The contribution from other countries is assumed to have reduced by 13 %, and by 18 % for international shipping.

H2040 – This represents a high ambition scenario with technological measures applied to the baseline to abate air pollutants. This includes the electrification of road transport and the power sector, leading to substantial reductions in NO_x emissions. It also includes very high ambition technological measures applied to agricultural NH_3, with a total abatement of 44 ktonnes NH_3 from this sector. These measures include low emission spreading, rapid incorporation, slurry tank covers and the use of urease inhibitors. Given the challenge in reducing NH_3 from agriculture this is likely to be close to the maximum feasible reduction from technical measures. Despite this large NH_3 abatement for agriculture, the total NH_3 reduction is lower due to increases for other sectors. These are mostly small other than a large increase in emissions (15 kt) from anaerobic digestion (AD) and digestate spreading. AD is expected to grow substantially in the UK and forms part of the UK's Net Zero (BEIS, 2021) and Biomass strategies (DESNZ, 2023). NH_3 emissions from this process and the spreading of digestate is an area of growing concern. The same assumptions as B2040 are taken for other countries and international shipping.

The total UK emissions for each scenario are provided in Table 2.

3. Results

3.1. Comparison of models

Fig. 2 shows the N_r deposition estimates for all three models in 2018 (CBED estimates the average over 3 years, in this case 2017–2019) and Fig. 3 shows the resulting AAE maps. There are clear differences between each model, with EMEP4UK providing the lowest estimates and CBED the highest. The total UK deposition budgets are shown in Fig. S1 and split between wet and dry deposition of NH_x and NO_x for EMEP4UK and UKIAM, and total NH_x and NO_x for CBED.

While the models provide a range of deposition estimates across the

Table 2
Total UK air pollutant emissions (in kt yr^{-1}) for each scenario.

Scenario	NH_3	NO_x
B2018	274	788
B2040	274	461
H2040	245	385

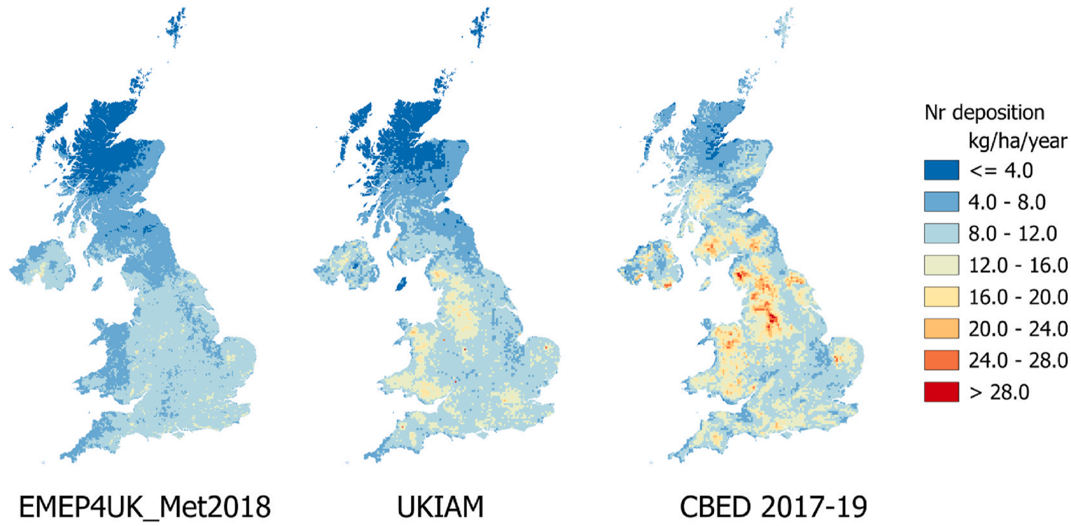

Fig. 2. Total reactive N deposition across the UK in 2018 by different models.

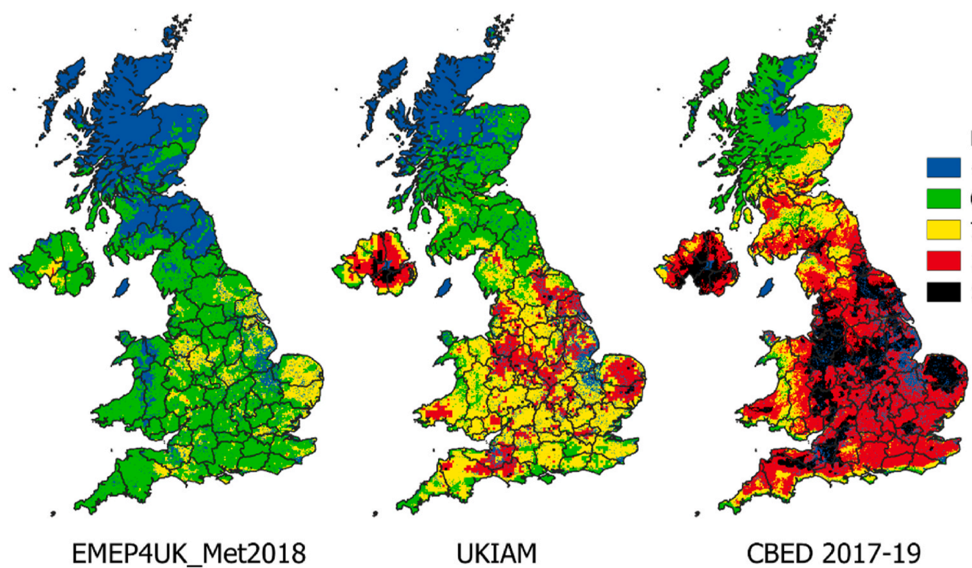

Fig. 3. Average accumulated exceedance for all habitats for B2018 for each model.

country, the greatest differences occur in areas of higher altitude and precipitation (e.g. much of Wales, the Peak District, Pennines and Lake District in England).

Deposition is complex in these areas and can occur through different complex processes as discussed in Section 1.1. The use of bulk rather than wet-only deposition measurements in the mapping of wet deposition is one reason for the higher deposition estimates given by CBED. Bulk deposition measurements are known to overestimate wet deposition due to contamination by dry deposition sources (Cape et al., 2009). Wet-only deposition sensors are designed to solve this issue however have not been as widely used. Another factor is that CBED includes occult deposition not currently accounted for in ACTMs like EMEP4UK or FRAME (which underpins UKIAM). Additional uncertainties in CBED arise from the combination of annual average concentrations with annual average meteorology (e.g. Schrader et al., 2018).

The seeder-feeder enhancement, which is in a simplified form accounted for in the FRAME source-receptor relationships, is the main reason why UKIAM estimates are higher than EMEP4UK in these areas. However, the magnitude of the enhancement is both highly uncertain (Cowan et al., 2022) and in reality the concentration enhancement in the rained out orographic cloud is likely to vary significantly in time and space depending on local topography and rainfall, and upwind emissions.

While there is better agreement between the models in lowland areas, the uncertainty here is still significant. This partly reflects the uncertainty and associated variability in dry deposition schemes (e.g. Flechard et al., 2011).

The range in deposition has an impact on the evaluation of exceedances of CLs. Table 3 shows the AAE and percentage area in exceedance for each model. The AAE varies by an order of magnitude, from 1.2 to 9.1 kg ha^{-1} yr^{-1}, while the percentage area of in exceedance varies by a factor of 2.5, from 36.8 % to 88.8 %.

Fig. S2 shows the AAE and percentage area in exceedance for B2018 for each UK nation. Different conclusions can be drawn regarding the comparable scale of the problem between each region depending on which model is used.

Table 3 also includes EMEP4UK predictions using 2018 emissions but 2003 meteorology data. We use 2003 as an example of a year when meteorology conditions were different to those in 2018, with the contribution from other countries on mainland Europe particularly high.

Table 3
N_r deposition budget, Average Accumulated Exceedance (AAE) and % area of N-sensitive habitat in exceedance of critical load for B2018 as predicted by each model for the UK.

	EMEP4UK (2018 met)	EMEP4UK (2003 met)	UKIAM	CBED 17-19
N_r deposition (ktonnes)	182.6	172.3	212.3	273.9
N_r deposition on habitats (ktonnes)	66.9	68.9	104.2	156.1
AAE (kg.ha^{-1}yr^{-1})	1.3	1.2	4.5	9.1
% area in exceedance	36.8 %	38.2 %	60.9 %	88.8 %

This comparison with EMEP4UK using 2018 meteorology suggests that while meteorology is a factor in predicting deposition rates and the resulting exceedances, it is significantly less than the difference between models.

3.2. Projected change in deposition and exceedances

The range of deposition estimates between models leads to a range in the estimated benefit achieved by different emission reduction scenarios. This is illustrated in Table 4 where we show the change in total deposited N_r (a) across the UK and (b) on sensitive habitat areas only, and also the associated changes in AAE and percentage area in exceedance. Maps of the AAE for the B2040 and H2040 scenarios are shown in Figs. S2 and S3.

For the B2040 scenario, EMEP4UK predicts a reduction of 9.6 ktonnes of N_r on sensitive habitats, compared to 9.2 and 16.2 ktonnes for UKIAM and E4UK-Scaled, respectively. For the H2040 scenario the reduction predicted by EMEP4UK, UKIAM and E4UK-Scaled is 14.0, 16.8 and 27.3 ktonnes respectively.

The differences in deposition estimates result in differences in both exceedance metrics (AAE and percentage area) but also the change relative to the baseline. For the B2040, the AAE is 0.7 kg ha yr^{-1} for EMEP4UK compared to 3.75 and 7.47 kg ha yr^{-1} for UKIAM and CBED, respectively, while for the H2040 these values are 0.45, 3.07 and 6.34, respectively. Therefore there is an order-of-magnitude range for the AAE predicted for these scenarios. The range of around a factor 3 is seen for the percentage area in exceedance.

3.3. Path towards zero exceedance in England

We now focus on England in order to relate these results to the England N_r deposition and habitat protection targets. Our most ambitious scenario, the H2040, still leaves large areas of habitat in exceedance according to all models. We explore the degree of reduction in deposition required to eliminate all exceedance, and what the path to this point looks like, by reducing the B2018 deposition map by a uniform scaler across the UK until we reach zero deposition. Fig. 5 shows how the percentage area of habitat in exceedance of CL_{rec} changes in England as deposition is reduced uniformly. Fig. S6 shows the equivalent plots for the UK.

In reality the spatial distribution of deposition will change in future and does so for our future scenarios (B2040 and H2040). However, these plots provide a meaningful illustration of the degree of change required in order to significantly reduce the exceeded area of each habitat. The markers on each plot indicate the outputs of each scenario. In most cases these markers lie on the line of the corresponding model, showing that the plots are representative of the change in exceedance as deposition is reduced, at least for the scenarios assessed here. The EMEP4UK scenario markers for B2040 and H2040 are further along the x-axis than those for UKIAM and E4UK-Scaled, indicating a greater sensitivity to the emission reductions in the scenarios.

The shaded area indicates the range in model outputs. This range is large for all habitats, only converging where exceedances start at or near 100 % or tend to zero where the deposition has been reduced substantially.

The rate at which the area in exceedance decreases varies between habitats. Woodland habitats such as managed deciduous, oak, beech and unmanaged mixed woodlands require greater reductions in deposition before significant gains are made in reducing the exceeded area, due to the enhanced dry deposition to forest compared to less aerodynamically rough vegetation.

The figure shows how the percent reduction in deposition predicted by one model can provide a significantly different estimate of the change in area of exceedance compared to what is predicted by a different model with the same percentage reduction in deposition. Despite the uncertainty in deposition, it is clear that in order to protect the majority

Table 4
N_r deposition budget, Average Accumulated Exceedance (AAE) and % area of N-sensitive habitat in exceedance of critical load by 2040 and change relative to 2018 for the 2040 baseline and High scenario for the UK. The percentages given in parentheses for the change in deposition and AAE is the % reduction relative to B2018.

		EMEP4UK (2018 met)	UKIAM	E4UK-Scaled[a]
B2040	**N_r deposition (ktonnes)**	164.2	180.8	233.5
	ΔN_r deposition (ktonnes)	−28.7	−31.5	−40.4
	As NH_x (ktonnes)	−3.9	−2.3	−5.5
	As NO_x (ktonnes)	−24.9	−29.2	−34.9
	N_r deposition on habitats (ktonnes)	57.3	95.0	139.9
	ΔN_r deposition on habitats (ktonnes)	−9.6 (−14 %)	−9.2 (−9 %)	−16.2 (−10 %)
	AAE (kg ha^{-1} yr^{-1})	0.7	3.75	7.47
	ΔAAE (kg ha^{-1} yr^{-1})	−0.60 (−46 %)	−0.75 (−17 %)	−1.63 (−18 %)
	% area in exceedance	29.8 %	54.9 %	83.8 %
	Δ% area in exceedance	−7 %	−6 %	−5 %
H2040	**N_r deposition (ktonnes)**	151.7	165.7	214.8
	ΔN_r deposition (ktonnes)	−41.2	−46.6	−59.1
	As NH_x (ktonnes)	−12.6	−12.2	−19.3
	As NO_x (ktonnes)	28.6	−34.5	−39.8
	N_r deposition on habitats (ktonnes)	52.9	87.4	128.8
	ΔN_r deposition on habitats (ktonnes)	−14.0 (−21 %)	−16.8 (−16 %)	−27.3 (−17 %)
	AAE (kg ha^{-1} yr^{-1})	0.45	3.07	6.34
	ΔAAE (kg ha^{-1} yr^{-1})	−0.85 (−66 %)	−1.43 (−32 %)	−2.76 (−30 %)
	% area in exceedance	25.8 %	51.9 %	80.8 %
	Δ% area in exceedance	−11 %	−9 %	−8 %

[a] E4UK-Scaled is used as a proxy for CBED for the future scenarios.

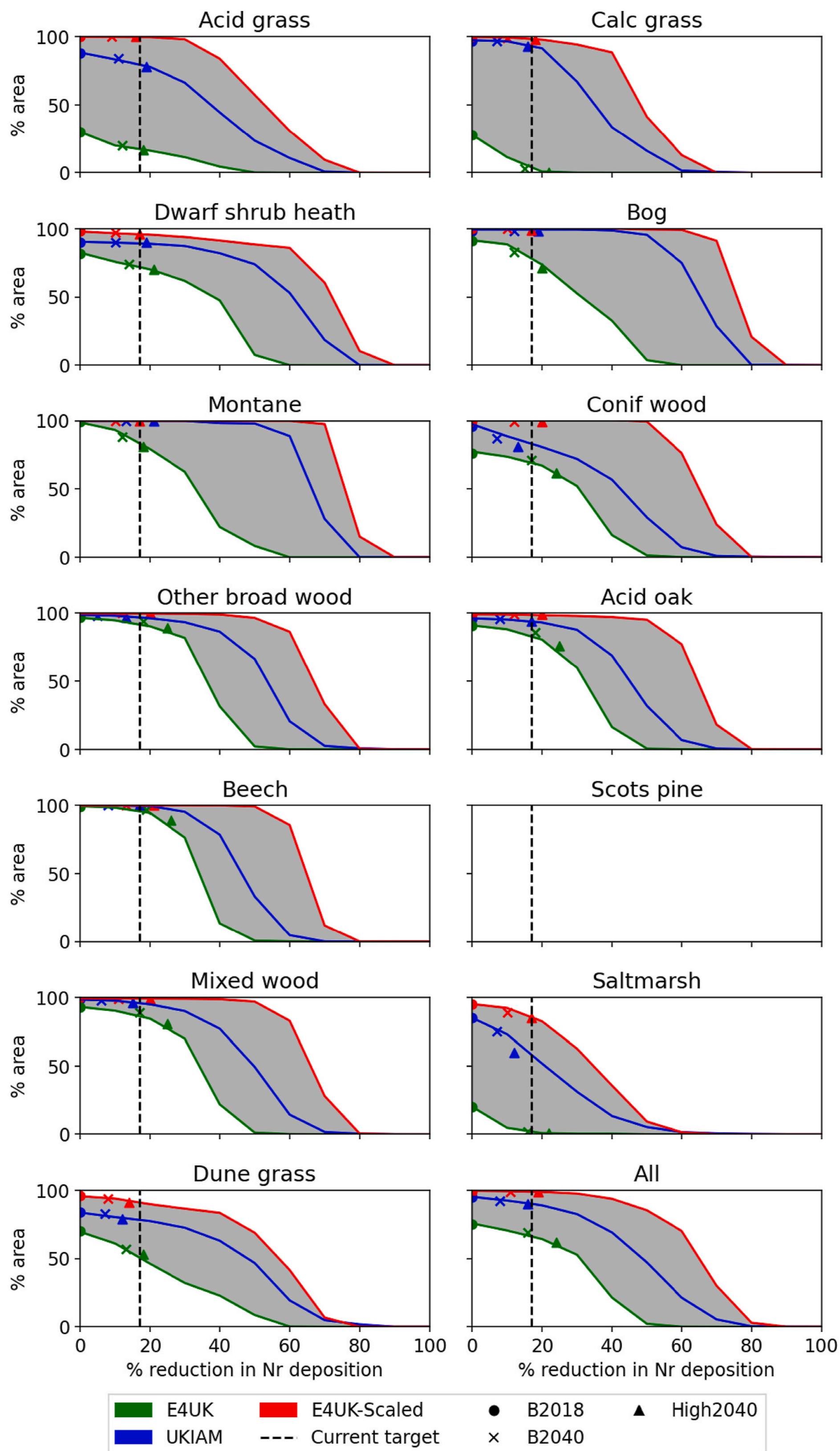

Fig. 5. Percentage area in exceedance of CL_{rec} in England against percentage reduction in N_r deposition for each habitat and for all habitats. The plotted lines are derived by reducing N_r deposition evenly across England a percentage point at a time and recording the percentage area in exceedance. The shaded area is an indication of the degree of uncertainty as estimated by the range in model estimates. The markers indicate the position of each scenario on the plot for each model. The Scots pine plot is empty for England as it exists in Scotland only.

of habitat areas a greater reduction in deposition is needed than the 17 % target set in the Clean Air Strategy (Defra, 2019) indicated by the black dashed line. For all habitat areas (lower right plot in Fig. 5), with a reduction of 17 % in deposition the area in exceedance is predicted to be 66 %, 90 % or 99 % for EMEP4UK, UKIAM and E4UK-Scaled, respectively.

Both EMEP4UK and E4UK-Scaled predict that the H2040 achieves a reduction in deposition equal to or greater than 17 % on these habitats, with UKIAM just short at 16 % (Table 4). There are also protected sites on priority habitats which can benefit from local measures to further decrease N_r deposition (Dragosits et al., 2020), however this is not the case for broader habitats which cover large areas.

The percentage reduction in deposition needed to remove all exceedances of CLs varies between 50 % for EMEP4UK and 90 % for E4UK-Scaled, with UKIAM on 80 %. The ambitious technological scenario, H2040, achieves a range of 16–22 % reduction.

3.4. *Taking a risk-based approach*

Using the risk-based approach (Woodward et al., 2022) described in Section 2.5 provides an evaluation that is not solely dependent on one model and accounts for the range in estimates for both deposition and CLs.

Fig. 6 shows the exceedance score areas for each habitat in the England for each scenario. There is considerable variation between habitats with woodland habitats in particular trouble. Scots Pine is entirely in Scotland and therefore no values are shown for England. The vast majority of area of these habitats are either marginal, likely or very likely in exceedance of its CL even for the H2040 scenario, with the plots on the far right showing the average across all habitats. Despite this, a steady improvement is seen for all habitats in terms of the proportion of habitat that is deemed likely (orange) or very likely (red) in exceedance, with the vast majority of the very likely category removed for H2040. Habitat area assigned to either the very unlikely (dark green) or unlikely (light green) in exceedance categories also see a steady progress for grasslands, dwarf shrub heath, salt marsh and dune grass. However not much progress is seen for these areas for woodland habitats, again reflecting the higher deposition rates to these habitats.

For England, the B2018 scenario has 12 % of habitat area either very unlikely or likely in exceedance, and 72 % likely or very likely in exceedance, with the remainder being marginal cases. This improves for B2040 and H2040, for which the proportion of habitat very unlikely or unlikely in exceedance is 18 % and 21 %, respectively. The proportion either likely or very likely in exceedance is 66 % and 59 %, respectively, with the very likely category down to 1 % for H2040.

Fig. S7 shows the equivalent plot for the entire UK where a greater proportion of habitat area is either very unlikely or unlikely in exceedance. This is due to lower exceedances in Scotland where N_r deposition is lower and a large proportion of habitat area exists. In the UK, the B2018 scenario has 46 % of habitat area either very unlikely or likely in exceedance, and 32 % likely or very likely in exceedance, with the remainder being marginal cases. This improves for B2040 and H2040, for which the proportion of habitat very unlikely or unlikely in exceedance is 52 % and 55 %, respectively. The proportion either likely or very likely in exceedance is 26 % and 23 %, respectively.

4. Discussion

The analysis presented here illustrates the wide range of deposition estimates that can be obtained from different UK models, EMEP4UK, UKIAM and CBED. The range in model estimates reflects the high uncertainty that exists both in modelled and measured deposition rates. This poses a problem when validating models and attempting to inform policy development and in particular target setting. Model estimates of current and future CL exceedances are used to guide policy development, however the range in deposition estimates between models often results in a range in exceedance estimates. This is true whether an area-based metric (e.g. percentage area in exceedance) or an exceedance-based metric (e.g. accumulated exceedance) is used (see Tables 3 and 4). While CBED is a semi-empirical model and therefore is not capable of future projections (the scaling method from Woodward et al. (2022) is used here to illustrate how CBED predictions could look like in 2040, denoted as E4UK-Scaled), both EMEP4UK and UKIAM are used to model future scenarios in support of policy and target setting.

4.1. *Uncertainties in N_r deposition*

CBED was designed specifically to be independent of emission estimates as it is based on the interpolation of measured concentrations in air and rain. By contrast, both EMEP4UK and UKIAM use emission estimates. For NH_3, the NAEI estimates an uncertainty of 16 % (Elliott et al., 2025) for the UK total, larger for the spatial attribution. Constraints based of earth observation have suggested that emissions may be underestimated by 30 % (Marais et al., 2021), but this approach itself is

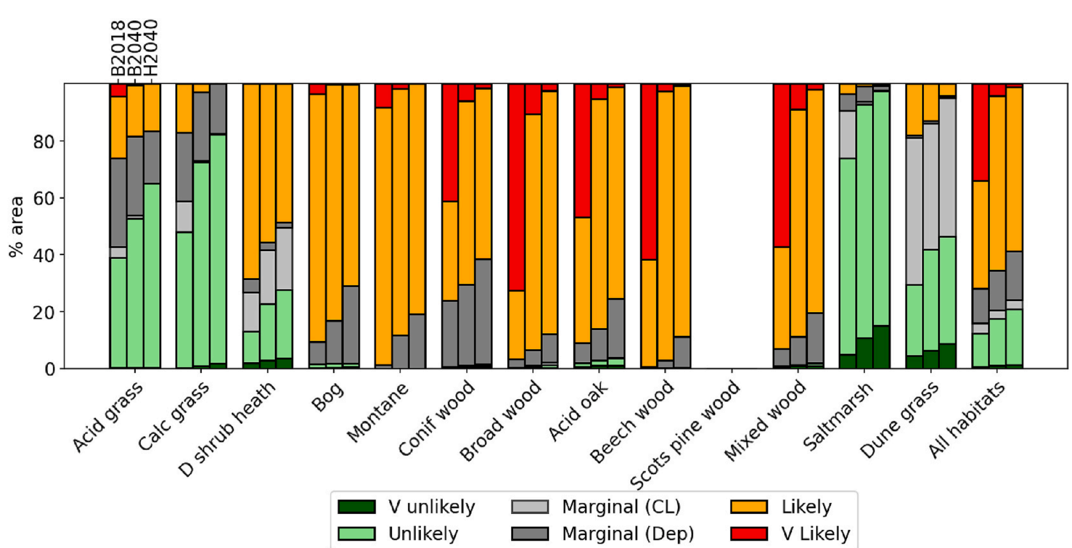

Fig. 6. Percentage area of each exceedance score assigned to each sensitive habitat in England for all scenarios. The derivation of the exceedance score areas is described in Section 2.5.

subject to similar uncertainties. On the other hand, CBED-specific uncertainties arise from the combination of annual average meteorology with annual average concentrations to derive deposition (e.g. Schrader et al., 2018).

Significant uncertainties exist in the parameterisation of dry and wet deposition in complex terrain (Cowan et al., 2022) and this accounts for much of the differences in the model estimates as orographic impacts on wet deposition are treated differently in the models.

Areas of higher altitude and precipitation are subject to additional atmospheric processes, such as the seeder-feeder effect in which rain from high level cloud falls through lower "feeder" clouds which typically contain higher concentrations of pollutants (Dore et al., 1992; Smith and Fowler, 2000). Accurate modelled prediction of deposition in complex terrain requires a quantitative understanding of occult deposition, orographic enhancement, the seeder-feeder effect, and highly localised rainfall. Model resolution is a key factor for resolving orographic effects, since greater resolutions tend to obscure topography. Cowan et al. (2022) estimate that the areas of complex terrain receive 1.4 and 2.5 times greater deposition than areas of simple terrain – that is, deposition rates are likely 1.4 to 2.5 higher than ACTMs currently predict. This enhancement is reflected to different levels in the different measurement approaches and it is challenging to conclusively judge which is closer to the truth because reliable measurements at high altitude are lacking. Wet deposition estimates are particularly variable and uncertain for mountainous areas, where it is often challenging to maintain equipment to monitor meteorology and the chemical composition of precipitation. High winds reduce capture efficiency of deposition gauges. Until very recently, only two sites in the UK currently provided daily measurements of wet-only deposition. At other sites, wet deposition must be estimated from long-term bulk deposition measurements, which can overestimate wet deposition by 20–40 % (Cape et al., 2009), but current understanding is deemed too uncertain to apply correction procedures. Large uncertainties also exist in dry deposition quantification in areas of complex terrain (i.e. turbulence variability associated with irregular topographic features, such as mountains, coastlines, steep slopes, cliffs or heterogenous vegetation cover). Particular measurement techniques must be applied, for example measurement of occult deposition, i.e. the interception of cloud droplets by vegetation.

Model resolution is also a problem for dry deposition hotspots, which can occur at sub-grid scales of tens of metres near point sources such as poultry farms. Lower resolution models may infer that the average concentration of a large grid cell is too small to cause exceedances of CLs, whilst a higher resolution model might identify areas of CL exceedance within that grid cell.

It should also be noted that organic forms of nitrogen are not currently included in any of the deposition estimates (measured or modelled), but can contribute 20–40 % to wet deposition (Cape et al., 2005, 2012). The contribution of the organic component varies significantly between countries and regions across the globe (Cornell, 2011), more research is needed to understand the spatial variation within countries (Cape et al., 2011). While we have crude estimates for dissolved organic nitrogen, the dry deposition of organic nitrogen compounds in the aerosol, though ubiquitous (Kiendler-Scharr et al., 2016) is even less well estimated.

4.2. The case for more ambitious targets

Despite the uncertainty in our estimates, it is possible to conclude from the analysis that a greater level of ambition is needed than the UK government's current 17 % reduction in deposition target if the vast majority of habitat area is to be protected in England. Our analysis suggests that achieving this target (here represented by the H2040 scenario) would result in only 1–34 % of habitat area below their CL (Fig. 5). While the risk-based approach (Fig. 6) predicts that only 21 % is very unlikely or at least unlikely to be in exceedance, with the remaining area either marginal, likely or very likely in exceedance.

Despite this, habitats can benefit from any reduction in deposition even when CLs remain in exceedance (e.g. Stevens et al., 2011; Armitage et al., 2014). Therefore, reaching the 17 % target will still deliver some benefit in reducing the pressure on sensitive habitats. This is reflected in the reduction in the accumulated exceedance (Table 4) and the proportion of area at greatest risk of continued high exceedance (Fig. 6) for the H2040 scenario. It should also be noted that ambitions that go beyond the Clean Air Strategy have been expressed. Through Target 7 of the Kunming-Montreal Global Biodiversity Framework (CBD, 2022) the UK, together with >180 other governments, declared its intention to reduce "pollution from all sources by 2030, to levels that are not harmful to biodiversity and ecosystem functions and services". Taken literally, this would imply completely eliminating CL exceedances by 2030.

To achieve a more ambitious target will require additional measures. In the UK, NH_3 emissions from agriculture is the main contributor to N_r deposition and CL exceedances (Woodward et al., 2022). The majority of these emissions is attributed to meat and dairy production (Defra, 2024), therefore reducing meat and dairy production could lead to significant reductions in NH_3 emissions (Leip et al., 2023). A reduction in meat and dairy is recommended in the UK's National Food Strategy (Dimbleby, 2021) to provide healthier diets, meet climate targets and reduce the impact on nature. The UK's Climate Change Committee also advise that a reduction in meat and dairy production is necessary to meet the UK's Net Zero target (CCC, 2020). Further exploration is needed of the synergies that exist between reducing the impact of NH_3 emissions, climate ambitions and healthy diets, for example see Leip et al. (2023).

A reduction in deposition of between 60 and 90 % would be required to eliminate all exceedances. This would require a significant increase in ambition. A significant reduction in the contribution from non-UK sources would also likely be necessary. UKIAM estimates the contribution from other countries and international shipping to the UK total N_r deposition in 2018 as 26 % and 6 %, respectively.

Finally, it is worth noting the limitations of CL exceedances as a metric when used to assess the harm caused by N_r deposition. Critical Loads are typically derived from experiments which are not able to capture the impact of long-term accumulation of N in the soil. Eliminating CL exceedances would not by any means guarantee that habitats recover from changes and have already occurred. Similarly, there is strong evidence that per kg of N_r deposited, gaseous NH_3 dry deposition is more detrimental than wet deposition (Sheppard et al., 2011), which is not reflected in the current CL methodology. However, CLs remain a useful metric of the varying resilience of habitats to N_r deposition and are therefore helpful guiding policy.

4.3. Implications for broader habitat protection targets

Consideration is needed regarding the condition assigned to habitat areas that are in exceedance of their CLs within the context of broader targets. For example, England's "30 by 30" target (Defra, 2023), also derived from the UNEP's Convention on Biological Diversity's Global Biodiversity Framework (CBD, 2022). This target sets out to protect 30 % of land in England from "loss or damage to important biodiversity values" by 2030. Another example is England's target to restore or create more than 500,000 ha of a range of wildlife-rich habitats outside of protected sites by 2042 (Environment Act 2021 (https://www.legislation.gov.uk/ukpga/2021/30/)).

We have not accounted for the increase in habitat area in our future scenarios, i.e. the area of each habitat remains the same from 2018 onwards. In reality we expect an increase in these habitat areas resulting from these targets and from climate mitigation measures such as woodland creation and peatland restoration. However, given the widespread exceedances across the UK, we expect that the majority of habitat area considered by these targets will continue to be under pressure from eutrophication and as a result continue to experience gradual changes in flora and fauna. This poses the question as to whether these areas can reasonably be considered "restored" or "protected" in the long term without significant progress in reducing the impact of N_r deposition.

It may also be necessary to consider habitat-specific targets. There is a clear and significant variation in CL exceedance for each N-sensitive habitat considered here (e.g. Figure S5 and Fig. 6). Woodland species are particularly under pressure and will require greater policy ambition than, for example, acid and calcareous grasslands to achieve significant increases in areas no longer harmed by N_r deposition. If the impact of N_r deposition was to be considered within the evaluation of broader targets, a habitat-specific approach would be necessary to ensure progress is made across all habitat types.

4.4. Relevance to other countries and regions

These uncertainties in deposition measurements and modelled predictions are not unique to the UK (e.g. Williams et al., 2017; Walker et al., 2019). International negotiations to reduce air pollution impacts depend on model estimates to inform national targets. There is recently an increased emphasis on NH_3 by the UNECE's CLRTAP due to the limited progress in abating these emissions. New targets are being developed for ecosystem protection from N_r deposition under the convention, making the accuracy of the assessment of N_r deposition and CL exceedances an issue of international concern. Our analysis for the UK and each UK nation demonstrates the importance of considering the uncertainty in estimates and the range of predictions available from different models. This also applies to existing international targets such as the European Commission's target of a reduction of 25 % in CL exceedances by 2030 relative to 2005 levels (European Commission, 2022b). While considerations are ongoing regarding a 50 % reduction target for accumulated exceedances for the Gothenburg protocol revision (TFIAM, 2024).

4.5. Using the exceedance score approach

By using the exceedance score approach outlined in Woodward et al. (2022) we are able to demonstrate that our scenarios make steady progress towards reducing the risk of the harm caused by N_r deposition for each habitat, despite the significant range of estimates between models. The method could be used to derive targets for policy development. Our scenario analysis suggests that eliminating the proportion of habitat area at greatest risk (very likely in exceedance) may be an achievable target for the UK and England only, with only a small proportion of habitat area assigned this category for the H2040 scenario. Targets within each nation could also be set for the proportion of habitat area very unlikely or unlikely to be in exceedance. Together these would provide targets which reduce the proportion of habitat area at greatest risk of harm, while also increasing the proportion unlikely to be caused harm.

5. Conclusions

There is large uncertainty in estimates of reactive nitrogen (N_r) deposition in the UK. This was reflected in the large range in model predictions, illustrated here by comparing three models used to inform policy in the UK: EMEP4UK, UKIAM and CBED. This range in predictions makes a big difference for future scenario assessment, where the impact of different policy measures was assessed by predicting their impact on deposition rates. Scenario modelling is a key element of informed policy development in the UK (e.g. ApSimon et al., 2023), and also plays an important role in international negotiations of national air pollution emission ceilings, e.g. the Gothenburg Protocol. While we have assessed the UK here, with a particular focus on England, the conclusions of this paper are likely relevant for other countries. The UKIAM model uses the same approach as the GAINS model, while EMEP4UK is a high resolution implementation of the EMEP model, both of which are used to inform CLRTAP negotiations.

We show that the range of model predictions results in a large range in predicted critical load (CL) exceedances. A significant range was also seen for the degree of improvement predicted for future scenarios, with the rate of improvement often of most interest to policymakers. This range in predictions poses a challenge for developing sensible targets to reduce the harmful impacts of eutrophication driven by deposition of atmospheric air pollutants. Despite this, our results show that a greater level of ambition is required to reduce these harmful impacts if the majority of habitat area is to be protected. For example, England's Clean Air Strategy target of a 17 % reduction in N_r deposition on sensitive habitats would leave 66–99 % of N sensitive habitat area in exceedance according to the modelled range considered here.

Removing all exceedance in England and the UK as a whole would require a 60–90 % reduction in N_r deposition on these habitats. Achieving a reduction of this order would require a step-change in ambition, both within the UK and for other countries which contribute a significant proportion, regarding NH_3 abatement. Further reductions are possible by considering non-technical measures such as reductions in livestock production. Such an approach has clear synergies with Net Zero policy which is an area of ongoing research.

Our risk-based approach provides a means to assess current and projected CL exceedances while accounting for the range in deposition estimates and uncertainty in CL assessment. The approach could be used to develop more robust targets, rather than depending on a single, highly uncertain estimate of CL exceedance.

CRediT authorship contribution statement

Huw Woodward: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elizabeth Ramos Fonseca:** Writing – original draft, Conceptualization. **Tim Oxley:** Writing – review & editing, Software, Methodology, Conceptualization. **Ed C. Rowe:** Writing – review & editing, Resources. **Massimo Vieno:** Writing – review & editing, Software, Resources, Methodology. **Eiko Nemitz:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Helen ApSimon:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

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Glossary

Anaerobic digestion (AD)
Average Accumulated Exceedance (AAE)
Atmospheric Chemistry Transport Model (ACTM)
Convention on Long-range Transboundary Air Pollution (CLRTAP)
Concentration Based Estimated Deposition (CBED)
Critical Loads (CLs)
European Monitoring and Evaluation Programme (EMEP)
European Nature Information System (EUNIS)
Weather Research and Forecasting (WRF)
Fine Resolution Atmospheric Multi-pollutant Exchange (FRAME)
Joint Nature Conservation Committee's (JNCC)
National Atmospheric Emission Inventory (NAEI)
Nitrogen Decision Framework (NDF)
UK Eutrophying and Acidifying Pollutants (UKEAP)
UK Integrated Assessment Model (UKIAM)

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.121519.

Data availability

Data will be made available on request.

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