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Modelling future impacts of air pollution using the multi-scale UK Integrated Assessment Model (UKIAM)

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Abstract: Integrated assessment modelling has evolved to support policy development in relation to air pollutants and greenhouse gases by providing integrated simulation tools able to produce quick and realistic representations of impacts without needing to re-run complex atmospheric dispersion models. The UK integrated assessment model has been developed to investigate cost-effective strategies for reducing UK emissions by integrating information on projected UK emissions of SO_2, NO_x, NH_3, PM_{10} and $PM_{2.5}$, atmospheric dispersion, criteria for protection of ecosystems, urban air quality and human health, and data on potential abatement measures to reduce both emissions and costs. We describe the multi-scale model structure, UK emissions sources, atmospheric dispersion of emissions, implementation of abatement measures, dynamic integration with European-scale modelling, and environmental impacts. The model generates outputs which are used to evaluate alternative strategies in relation to emissions, deposition patterns, air quality metrics and ecosystem critical load exceedance. Finally, we present a selection of scenarios in relation to the 2020 baseline projections and identify potential further reductions beyond those currently being planned.

Keywords: UKIAM; Integrated assessment; model integration; air pollutants

Background

Integrated assessment modelling has evolved over recent decades in order to support policy development in relation to air pollutants, and more recently greenhouse gases, by providing integrated simulation tools able to produce quick and realistic representations of impacts without needing to re-run complex atmospheric dispersion models with long run-times. The achievements of integrated assessment modelling in relation to policy development aimed at air pollution control, health and climate change at the European scale are highlighted by Hordijk and Amann (2007).

The UK integrated assessment model, UKIAM [Oxley *et al.*, 2003] was developed to investigate cost-effective strategies for reducing UK emissions which maximise improvements in environmental protection in the UK while complying with future UK emission ceilings imposed to reduce transboundary air pollution in Europe. It brings together information on projected UK emissions of SO_2, NO_x, NH_3, PM_{10} and $PM_{2.5}$; atmospheric modelling of concentrations and deposition including imported contributions; criteria for protection of UK ecosystems, urban air quality and human health; and data on potential abatement measures to reduce both emissions and costs. UKIAM was one of the first national-scale integrated assessment models to be developed after the multi-pollutant multi-effect Gothenburg protocol [UNECE, 1999] to investigate compliance with emissions ceilings for 2010, and was designed to be nested within the ASAM model [ApSimon *et al.*, 1994; Warren & ApSimon, 1999; 2000] which addresses the European scale to create an integrated hierarchical environment able to capture changes at both European and national scales [Oxley & ApSimon, 2007].

UKIAM has since been extended to include greenhouse gas emissions and other environmental indicators to give a wider view of the policy implications of different control strategies - particularly interactions between air quality and climate policy [ApSimon *et al.*, 2009]. Whereas several other countries have implemented scaled-down version of the GAINS model (http://gains.iiasa.ac.at/) at a national level (http://niam.scarp.se/), UKIAM remains an independent model paralleling GAINS but deploying UK modelling expertise at 5km resolution over the UK, in particular the FRAME model [Fournier *et al.*, 2004; Dore *et al.*, 2007]. A difficulty with European-scale models is that they can only addresses urban air quality crudely, whereas a detailed sub-model addressing road transport and urban air quality, the BRUTAL model [Oxley *et al.*, 2009; 2012], has been developed and incorporated within UKIAM to explore future compliance with air quality legislation and roadside concentrations.

UKIAM provides a modelling framework for addressing future scenarios by drawing on data and models developed by a variety of national research organisations. UKIAM has the capability to investigate the effects of behavioural change as well as purely technical measures; and merges a range of scales from European to the road-side. To avoid time-consuming runs of atmospheric models, UKIAM uses pre-calculated source-receptor relationships derived from atmospheric modelling to estimate the response of baseline concentrations and deposition to changes in different sources both within and outside the UK. Thus the atmospheric models (the European-scale EMEP model [Simpson *et al.*, 2003], the UK scale FRAME model, and a high resolution application of the Gaussian PPM model [Gonzales del Campo, 2003]) have been run externally to develop the baseline and source-footprints used within UKIAM and BRUTAL. This facilitates rapid assessment of a range of future scenarios from which to select the most promising for detailed evaluation and comparison with other models.

FIGURE 1

Methodology

Figure 1 provides an overview of the multi-scale UKIAM modelling framework, highlighting:

- Baseline UK emissions which are provided by the National Atmospheric Emissions Inventory (NAEI) (www.naei.org.uk), with future emission scenarios based upon Updated Energy and traffic Projections (UEP) developed by the UK Government;
- Emissions from shipping, which span the boundary between the UKIAM and ASAM, have been quantified spatially by AMEC Environment & Infrastructure UK (http://www.amec-ukenvironment.com/);

- Abatement measures and associated costs have been developed by AMEC in a Multi-Pollutant Measures Database [AMEC, 2009a], and by NARSES [Defra, 2001] and North Wyke Research for agricultural measures;
- Atmospheric dispersion of emissions is captured by FRAME for UK sources, by EMEP for non-UK sources, and by a high resolution application of the Gaussian PPM model for NO_x and $PM_{10/2.5}$. FRAME and EMEP capture all relevant atmospheric chemistry whereas PPM assumes no chemistry;
- Spatial definition of ecosystems and ecosystem critical loads for acidification and eutrophication are provided by the Centre for Ecology & Hydrology (CEH) [Hall *et al.*, 2003; 2008];
- Spatial definition of designated areas (SSSIs, SACs, SPAs) and critical loads of acidity and eutrophication for designated features and habitats are provided (via CEH) by the UK Government Joint Nature Conservation Committee (JNCC) (http://www.jncc.gov.uk/);
- The BRUTAL sub-model provides high resolution modelling of UK road transport within UKIAM, and quantifies relevant air quality metrics.

Developments to the model consider a wider range of pollutants (SO_2, NO_x, NH_3, PM_{10}, $PM_{2.5}$, CO_2, N_2O and CH_4) to facilitate analysis of simultaneous effects of abatement measures on a combination of pollutants, and comparison of future scenarios with respect to changes in greenhouse gas emissions as well as human exposure to air pollution, urban air quality, and effects on natural ecosystems. Simultaneously ASAM has been redeveloped to allow the UK scale modelling to be embedded in the wider European-scale context. Utilising EMEP source-receptor relationships based upon projected 2010 emissions and using an average of five meteorological years (see http://www.emep.int/), ASAM quantifies the imported contributions of all EMEP pollutants (NO_x, SO_x and NH_x deposition; secondary inorganic aerosols, particulate matter, Ozone, etc.).

FIGURE 2

Shipping emissions – at a finer grid resolution (5km) than provided by EMEP (50km) – cover a 200 nautical mile radius from the UK coastline (see Figure 2). These emissions fall partly into the FRAME-UK domain and partly into the FRAME-Europe domain. Business as usual (BAU) emissions are used, together with a scenario capturing Annex VI of the MARPOL Convention to abate emissions from international shipping [AMEC, 2009b]. Recent ratification of Annex VI will result in major decreases in the emissions of SO_2 from international shipping due to a cap of 0.1% on the sulphur content of bunker fuel in Sulphur Emission Control Areas (SECA) which include the North Sea and the English Channel. MARPOL means that by 2020 international shipping will no longer be a significant source of SO_2 but emissions of NO_x will continue to be comparable with total UK emissions. Use of the finer resolution emissions better represented shipping lanes in the English Channel, avoiding the co-location of shipping emissions with coastal grid squares. MARPOL was found to result in a significant decrease (23%) in sulphur deposition in the UK for 2020 [Dore *et al.*, 2007].

Background concentrations of PM_{10} and $PM_{2.5}$ from non-anthropogenic sources which are not represented in the national inventories or by other UKIAM sources are also incorporated so that assessment of concentrations of particulate matter includes *all* contributions, both natural and anthropogenic. In order to maintain consistency, the UKIAM utilises equivalent spatial definitions of sea-salt, secondary organic matter (SOA) [Metcalfe *et al.*, 2001], and calcium and ferrous dust as used by the NAEI. These, combined with the contribution of water to the overall mass of PM as determined by EMEP [Tsyro, 2005] define background particulates as utilised by UKIAM. Figure

3 presents the spatial distribution of these background concentrations together with a breakdown by population-weighted mean concentrations of the individual components.

FIGURE 3

Finally, although the UKIAM was originally developed to determine optimised abatement strategies for the UK [Oxley *et al.*, 2003], the model is now used predominately in 'scenario' mode. Several factors have contributed to this change in the use of the model. Firstly, updates to the model have shifted the baseline from 2010 to 2020, with many measures available in 2010 assumed to be included as business-as-usual in the 2020 baseline. Secondly, whereas the GAINS model spans national (political) boundaries and maintains an underlying purpose of 'facilitating negotiations' through assessment of optimal and equitable abatement strategies, the UKIAM operates *within* a national boundary and is therefore of more utility in assessing alternative policy scenarios reflecting objectives of the national government. And thirdly, high resolution developments to address urban air quality and roadside concentrations of pollutants render it increasingly complex to determine what constitutes an 'optimal' strategy.

UK Emission Sources

In order to facilitate a focussed approach, UKIAM defines 65 distinct source categories reflecting different SNAP sectors or sub-sectors as described below. The baseline emissions, aggregated broadly into power generation, non-power combustion, industry, road transport, off-road transport and agricultural or natural, are summarised in Table 1:

1. *Combustion in Energy Industries*: Major power stations are treated individually, small power stations are treated collectively as a spatially distributed source, as are refineries and offshore oil and gas.
2. *Non-industrial Combustion*: Domestic combustion is further split into fuel usage (gas, oil and coal); public sector combustion is treated as a single dispersed source.
3. *Combustion in Manufacturing Industries*: The main industrial sectors are handled as separate sources (cement, iron and steel, sinter production, brick manufacture etc.), the remainder categorised together as 'Other Industrial Combustion'.
4. *Production Processes*: Treated as a single dispersed source.
5. *Extraction and Distribution*: A single dispersed source.
6. *Solvent Use*: Mainly VOC emissions which are not at present captured by UKIAM.
7. *Road Transport*: Petrol and diesel cars, LGVs, HGVs and buses are handled as separate sources by the BRUTAL sub-model
8. *Other mobile sources and machinery*: Off-road emissions include shipping, aircraft, railways, agricultural and industrial separately, with the remainder assumed to be domestic.
9. *Waste treatment and disposal*: is included as a single dispersed source.
10. *Agriculture*: Seven categories of livestock are included based upon agricultural census data [EDINA, 2009], with fertiliser emissions treated separately.
11. *Natural emissions*: Includes natural emissions as defined by NAEI.

An additional source category (Europe) is used in combination with ASAM to capture changes in imported contributions resulting from abatement strategies assumed elsewhere in Europe.

TABLE 1

The spatial definition of sources follows the methodology adopted by NAEI whereby normalised distribution matrices determine the spatial allocation of emissions (at 1km resolution) specified by official *Updated Energy Projections* in relation to source category and fuel type. In some cases the UKIAM sources explicitly reflect the fuel usage, for example, with separate sources for domestic combustion using coal, using oil, or using gas, where distinct spatial distributions are available for the different fuels. In other cases, eg. 'other industrial combustion', the spatial distribution specifies the distribution of total emissions and does not distinguish between fuel usage; for these sources it is necessary to maintain a record of the proportions of different fuels used so that abatement measures can be adjusted accordingly for the affected source (see Table 2).

Emissions from shipping are, however, treated differently to the NAEI. Whereas the national inventory reports coastal shipping only, the UKIAM necessarily requires all shipping emissions irrespective of whether they are 'reportable' or not. For this reason, and due to the poor spatial resolution of EMEP shipping data, the UKIAM integrates shipping emissions at 5km resolution (see AMEC (2009b)) for sea areas within 200 nautical miles of the UK, supplemented by EMEP representations (50km) for shipping beyond this distance.

TABLE 2

Abatement Measures

UKIAM represents a tool for rapid simulation and comparison of a large number of scenarios reflecting alternative strategies for controlling emissions. Technical abatement measures have been defined and incorporated into a Multi-Pollutant Measures Database giving percentage reductions in emissions achieved for each pollutant for a selected source, together with unit costs [AMEC, 2009a]. The database describes abatement measures for consideration in future policies such as future revision of the National Emission Ceilings Directive (NECD) (Directive 2001/81/EC) and the revision of the Gothenburg Protocol. The database addresses pollutants currently regulated under the NECD or due to be included in proposals for 2020 (NO_x, SO_2, VOCs, NH_3 and $PM_{2.5}$). Beyond Business-As-Usual (BAU) measures for ammonia have been developed using NARSES [Defra, 2001] and additional information from North Wyke Research (http://www.northwyke.bbsrc.ac.uk/).

A review of these measures in relation to the definition of sources within the UKIAM, assumptions about the uptake of measures included in baseline 2020 projections, compatibility with assumptions made by NAEI, and assumed fuel quality (eg. sulphur content), has resulted in a subset of these measures being incorporated into the UKIAM. In the case of power generation, the main UK power stations are treated individually in response to updated energy projections and assumed fuel mix across the sector. Furthermore, road transport is captured using the BRUTAL model, addressing both technical and behavioural abatement measures which supersede those defined in the multi-pollutant measures database provided by AMEC (2009a) (see, for example, Oxley *et al.* (2012)). The UKIAM thus applies abatement measures to the main sectors contributing to air pollutant emissions in 2020 (see Table 1): individual power stations, road transport, and industrial sources. Measures for other sources (eg. domestic combustion) require further analysis owing to different assumptions about existing boiler technologies and emission factors. Measures for NH_3 abatement from agriculture are documented elsewhere [Hasnain, 2009]. Table 2 summarises some of the industrial abatement measures available to UKIAM.

Thus, the emissions reduction (for each pollutant, *p*, where applicable) from each abatement measure for a given source, *s*, can be calculated as follows:

$$EmitReduction_{s,p} = BaseEmit_{s,p} \text{ X } FuelFraction_{s} \text{ X } Applicability_{s} \text{ X } Efficiency_{s,p}$$

where the fuel fraction determines the proportion of the UKIAM source affected where alternative fuels are captured by a single source (eg. Autogenerators); this fraction is based upon the fuel mix used to define *BaseEmit*.

The measures described above (including power stations, road transport and agricultural NH_3) combine to enable the UKIAM to assess pollution abatement measures for UK sources which contribute 90% of SO_2 emissions, 75% of NO_X emissions, 87% of NH_3 (agriculture only), 65% of PM_{10} and 68% of $PM_{2.5}$, based upon projected emissions in 2020. Inclusion of measures for off-road transport and public/domestic combustion would raise these percentages to >90%.

Although costs have been associated with most abatement measures, enabling scenarios to be specified which implement the least cost measures first, these costs are regularly subject to revision and therefore cannot be described here. Unlike European-scale modelling which, for the purposes of negotiating UN protocols or EU directives, requires consistent costing of measures in order to maintain appropriate equity between Member States, at a national scale governments may experience variations in, or revise, these costs.

Assuming least cost measures are implemented first, a variety of effects-based policy targets drive investigations of alternative abatement strategies. These targets include a requirement to achieve national emissions ceilings and to enhance urban air quality to avoid exceedance of air quality limit values. Although NECD targets for 2010 have been achieved in the UK [Wagner, 2010], more stringent targets can be expected in future revisions of the Directive. In relation to ecosystem protection (acidification and eutrophication) and health impacts, a 'gap closure' approach with varying ambition levels has been recommended by UNECE (2011) for incorporation into revisions of the Gothenburg Protocol.

The UKIAM quantifies total emissions of each pollutant following implementation of abatement scenarios (eg Table 1), quantifies exceedance of ecosystem critical loads (eg. Table 4), calculates the length of roads remaining *at risk* of exceeding air quality limit values (eg. Table 5), and derives a measure of health impacts (Years Of Life Lost) based upon background concentrations of $PM_{2.5}$ (eg Table 6).

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Atmospheric Dispersion

Data from FRAME is used to assess deposition of sulphur and nitrogen on different types of ecosystem at 5km resolution, and to quantify impacts upon secondary inorganic aerosols (NH_4, NO_3, SO_4). Dispersion of air pollutants is based upon source-receptor relationships calculated by FRAME that capture the effects of cross-pollutant atmospheric chemistry in relation to sulphur and nitrogen. The main features of FRAME are:

- 5x5 km^2 resolution over the British Isles (incl. the Republic of Ireland);
- Boundary gas and aerosol concentrations at the edge of the model domain are calculated with FRAME-Europe, using European emissions at 50 km resolution;
- Air column divided into 33 layers moving along straight-line trajectories in a Lagrangian framework with a 1^{o} angular resolution. The air column advection speed and frequency for a given wind direction is statistically

derived from radio-sonde measurements [Dore *et al.*, 2006]. Variable layer thickness from 1 m at the surface to 100 m at the mixing layer;

- Emissions are gridded separately by sub-SNAP sector for SO_2 and NO_x and by agricultural sector for NH_3 and injected into vertical model layers dependent on the sector.
- Point source emissions are treated with a plume rise parameterisation dependent on stack parameters (stack height, diameter, temperature and exit velocity) as well as the Pasquill-Gifford stability class [Vieno *et al.*, 2010].
- Vertical diffusion in the air column is calculated using K-theory eddy diffusivity and solved with the Finite Volume Method.
- Wet deposition is calculated using a 'constant drizzle' approximation driven by an annual rainfall map. A precipitation model is used to calculate wind-direction-dependent orographic enhancement of wet deposition [Fournier *et al.*, 2005].
- Five land cover classes (forest, moorland, grassland, arable, urban) and water are considered. A vegetation specific canopy resistance parameterisation is employed to calculate dry deposition of SO_2, NO_x and NH_3.
- The model chemistry includes gas phase and aqueous phase reactions of oxidised sulphur and nitrogen and conversion of NH_3 to ammonium sulphate and ammonium nitrate aerosol.

Calculating source-receptor matrices (SRMs) individually for different pollutants is in line with changes made by EMEP to calculate country SRMs on a European scale [EMEP, 2010]. This allows inclusion of 'cross terms' in the data set and permits assessment of questions such as: "*What is the influence of abatement of SO_2 emissions on concentrations of reduced nitrogen?"* or *"What is the influence of abatement of NH_3 emissions on formation of nitrate aerosol?"* The reduction of emissions of SO_2 for example may slow the formation of ammonium sulphate aerosol, resulting not only in decreases in wet and dry deposition of sulphur but also in a decrease in wet deposition of reduced nitrogen. However this reduction may be offset by increased concentrations of ammonia and dry deposition of reduced nitrogen [Erisman *et al.*, 1998]. The consequence is that emissions of primary pollutants may be correlated to effective *reductions* in concentrations of secondary pollutants. This concept of the emission of one pollutant effectively reducing concentrations of another is important to include if we are to consider the full range of effects associated with emission reductions. Emissions from the largest 20 point sources were treated as individual sources in FRAME and processed with a plume rise algorithm dependent on stack parameters. The most significant sources of SO_2 emissions are power stations and refineries which together account for 45% of UK emissions. These sources also contribute 26% of NO_x emissions whereas road transport contributes 31% of total UK NO_x emissions.

Finally, FRAME has been further developed to operate at 1km resolution, but due to excessive run-times it is not feasible to generate the source-receptor matrices required by the UKIAM. However, this does facilitate re-running selected UKIAM scenarios at increased resolution in order to better quantify impacts upon ecosystems. Hallsworth *et al.* (2007) found that simulations of ammonia concentrations at this finer resolution resulted in *lower* exceedance of critical levels at nature reserves than at 5km resolution. This was due to more accurate mapping of ammonia emissions and reduced incidence of co-location of source areas with sink sites.

TABLE 3

Atmospheric dispersion by the FRAME model addresses deposition rates and determines concentrations of secondary inorganic aerosols (SIA). In order to calculate concentrations of $PM_{10/2.5}$ and NO_x/NO_2 the UKIAM utilises source-receptor relationships derived from a high resolution application of the Gaussian PPM model [ApSimon *et al.*, 2001], assuming no chemistry in the dispersion process. Currently the UKIAM does not calculate concentrations of ozone since the source-receptor relationships from the FRAME model do not include ozone. Work is ongoing to develop source-receptor matrices based upon the EMEP4UK model, with subsequent versions of the UKIAM able to use data from either model and thus also directly address ozone concentrations [Vieno *et al.*, 2009].

At present therefore, derivation of NO_2 concentrations is handled by an extension of the relationship described by Oxley *et al.* (2009), which accounts for variations in total oxidant levels (including ozone) and allows for spatially variable fractions of primary NO_2 based upon the relative emissions rates of NO_x and primary NO_2 for each source. This approach has been shown to provide good agreement with measurements of NO_2 (See Figure 6). A summary of the different sub-models providing the dispersion calculations for each pollutant within the UKIAM framework is presented in Table 3.

Environmental Criteria

Human Health Impacts:

Health Impacts such as calculation of the loss in statistical life expectancy, 'Years Of Life Lost' (YOLL) or 'Daily Adjusted Life Years' (DALY) (see Amann *et al.* (2011)) are being routinely used to assess the overall health impacts of air pollution. The UKIAM calculates background and roadside concentrations of air pollutants in order to determine overall population exposure and population-weighted mean (PWM) concentrations. Population exposure to total $PM_{2.5}$ is converted to YOLLs (see below) which are used as a proxy for health impacts. This reflects the methods used by Pope *et al*. (2009) and preceding studies, and the ExternE project of the European Commission [Bickel & Friedrich, 2005]. The exposure-response relationships used by the UKIAM are based upon the Benefits Table database developed by Holland & Watkiss (2002) for the European Commission:

$$\text{YOLL} = 3.42\text{E-}04 * \textit{Exposure}$$

$$\text{where } \textit{Exposure} = \sum (\text{Concentration}_{(x,y)} * \text{Population}_{(x,y)})$$

where (x,y) refers to 1km resolution grid cells.

The spatial and temporal complexities involved in quantifying the *actual* exposure of individuals to air pollutants, and thus the health effects, is beyond the reach of an annualised integrated assessment model such as the UKIAM, although integrated assessment modelling is a useful component in more focussed epidemiological studies [Fecht, 2011].

Ecosystem Critical Loads:

Critical Loads are defined as the threshold level for the deposition of a pollutant above which harmful effects can occur in an ecosystem. Deposition above the critical load is termed *Critical Load Exceedance* and is typically used to assess the level of ecosystem protection from acidification and eutrophication [Hall *et al.*, 2003; Hall et al, 2008; RoTAP, 2012]. In the UKIAM detailed ecosystem and critical load data for the UK are combined with maps of deposition of sulphur and nitrogen derived using FRAME source-receptor relationships for different types of vegetation and freshwaters to calculate potential exceedances of critical loads. Maps of average accumulated exceedance (AAE) indicate the spatial variation across the UK and facilitate comparison of different scenarios, along with statistical data on overall exceedance for different ecosystems categories (see Table 4).

TABLE 4

FIGURE 4

Although useful for describing impacts nationally, this approach attaches equal importance to each ecosystem area, irrespective of whether it may be a Site of Special Scientific Interest (SSSI) or a European Natura 2000 site (which includes Special Areas of Conservation (SAC) designated under the EC Habitats Directive, and Special Protection Areas (SPA) protected by the EC Birds Directive). In order to overcome this, additional data has been incorporated into UKIAM describing the spatial distribution of different features and habitats within SSSI's, together with associated critical load data [Hall *et al.*, 2003]. Thus the model provides tabulated outputs of the number and area of features and habitats exceeded together with the potential magnitude of exceedances in relation to given deposition patterns.

Figure 4 provides a spatial representation of exceedances of site-specific critical loads based upon projected baseline emissions in 2020. However, whenever modelled exceedances are interpreted in relation to policy scenarios, it is important to ensure that the exceedances are calculated at an appropriate spatial resolution and temporal scale [Oxley *et al.*, 2011b].

Urban Air Quality:

The BRUTAL model [Oxley *et al.,* 2009] was developed as a high resolution module of UKIAM to capture enhanced roadside concentrations of air pollutants in urban street canyons. The model uses vehicle and technology-dependent emission factors aggregated, by the iMOVE model [Valiantis *et al.*, 2007], to represent an 'average' vehicle in a given vehicle mix for different roads. Applied across the UK road network these emission factors enable us to derive emissions from the bottom up, and to calculate the resulting concentrations for different types of road and traffic mix. Typical effects of street canyons in urban and city centres in enhancing roadside concentrations have been derived using ADMS-Urban [Vardoulakis *et al.*, 2007].

Gridded (1km) concentrations of NO_x and PM_{10} are calculated using a high resolution application of the PPM model. NO_2 concentrations are calculated using a quadratic equation that assumes conservation of total oxidant and NO_x with empirically derived parameters to reflect oxidation and photo-dissociation under different conditions [Oxley *et al.*, 2009]. This relationship has been extended to allow different degrees of convergence towards equilibrium determined by location, varying from roadside sites close to emissions sources to rural background sites where the chemistry is closer to the photo-stationary state [ApSimon & Oxley, 2010]. By nesting this model within UKIAM and ASAM it is possible to assess the peak local concentrations in urban street canyons which contribute to exceedance of urban air quality limit values and to evaluate abatement measures which influence air quality through affecting traffic emissions, vehicle mixes and traffic flows. Automatic source-apportionment highlights the relative contributions from local and distant sources, and provides the basis for linking air quality issues and traffic management at the local level with the policy requirements to comply with international agreements on transboundary air pollution and national emissions ceilings.Transboundary Contributions

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An additional source category is included in order to capture transboundary contributions to UK pollutant deposition rates and air quality. A single source category within the UKIAM cannot, however, effectively capture the spatial dimension of emissions changes in Europe; for example, an emissions reduction in The Netherlands will have a greater influence on the UK than an equivalent reduction in Eastern Europe. However, owing to greater model resolution and orographic enhancement, the FRAME model provides a significantly better spatial definition of the deposition patterns resulting from these transboundary influences than is available from the EMEP model [Oxley *et al.*, 2007; ApSimon & Oxley, 2010]. Reasonable agreement between the FRAME and EMEP deposition budgets for imported contributions [Dore *et al.*, 2009] provides conditions for dynamic integration with the ASAM model to capture the variable influence of nearby and remote European emissions sources. European scenarios (excluding UK) are thus modelled by ASAM to define the imported deposition budget, with this deposition spatially redistributed to reflect the FRAME representation of deposition from non-UK sources.

This multi-scale integration embeds UK emissions sources within the context of changing transboundary influences, facilitating analyses of UK abatement strategies in relation to different PRIMES emission scenarios (see, for example, Wagner *et al.* (2010)), the EU Thematic Strategy on Air Pollution (TSAP) and maximum realistic reductions across Europe. Figure 5 highlights the influence of alternative European emissions scenarios in relation to the UK baseline. The BAU2020 scenario incorporates EMEP CLE2020 (Current Legislation) emissions for non-UK sources, downloadable from http://www.ceip.at/. Scenarios P10CLE, P10TSAP and P10MRR reflect PRIMES2010 definitions of current legislation (see Wagner *et al.* (2010)), thematic strategy on air pollution and maximum realisable reductions, respectively, with P09CLE reflecting the preceding PRIMES2009 projection. NATCLE reflects national projections. Finally, P10MRRMFR reflects P10MRR combined with maximum feasible reductions (MFR) for both industrial and agricultural sources in the UK, ,with a speculative 'Beyond MFR' scenario which assumes further NO_X reductions from shipping to reflect the introduction of Nitrogen Emission Control Areas (NECA), significant replacement of domestic combustion and small power stations by renewable sources, and dramatic additional reductions in agricultural NH_3 emissions. This speculative scenario also highlights the cross-pollutant effects of atmospheric chemistry, with a marginal increase in SO_X deposition resulting from the reductions in NO_X and NH_3 emissions.

FIGURE 5

Validation

As described above, integrated assessment models involve the integration of multiple models and datasets each of which can be validated independently, as described below in the case of FRAME and the BRUTAL sub-model. In the context of UKIAM, the FRAME source-receptor matrices reflect necessary datasets in order to derive the impact of variations in emissions; the FRAME model is not re-run by the UKIAM. The BRUTAL model, however, utilises data generated by UKIAM in combination with its own treatment of road transport; in this case both models are run in combination. Thus, the UKIAM can be implicitly validated in relation to urban air quality through validation of the BRUTAL model. However, this validation can only address the *total* concentrations of air pollutants. It does not validate the source-apportionment of contributions to this total; this can only be achieved through comparison with alternative models and evaluation of variations between different models (see below).

In the case of the FRAME data, modelled calculation of 'footprints' of concentration and deposition from individual sources are subject to uncertainty because these are calculated based on the difference between two model simulations with often only small differences in total input emissions. These footprints are normalised and calibrated to bring the data in line with a standardised dataset using maps based on interpolation of measurements [Smith *et al.*, 2000]. A study of uncertainty in atmospheric transport modelling is addressed in detail by Page *et al.* (2004). In a model inter-comparison exercise for estimating the air concentrations and deposition footprints from a single power station, validation of the model against measurements showed that FRAME compared favourably with a more complex Eulerian model [Chemel *et al*., 2011; Carslaw, 2011a; Williams *et al.*, 2011].

In the case of the BRUTAL model, sensitivity studies have been undertaken to address cold start emissions, catalytic failures etc., and to ensure consistency with the NAEI emissions projections based on the same speed-dependent emission factors and vehicle categories [ApSimon & Oxley, 2010]. The model has been validated against measurements of NO_2 from London and national monitoring stations [Lennartz-Walker, 2010; Carslaw 2011b]. Figure 6 shows that there is good agreement between NO_2 and PM_{10} concentrations modelled by BRUTAL and measurements. The model has also been shown to perform well in relation to annual average concentrations when compared with other urban models such as ADMS [Carruthers *et al.*, 2010], the Pollution Climate Mapping (PCM) model [Stedman *et al.*, 2007] and alternative applications of CMAQ (eg. Carslaw & Beevers (2005)), as part of a model inter-comparison exercise carried out by Defra [Carslaw, 2011b]. An analysis of the cross-sectoral implications of alternative abatement strategies in road transport are reported elsewhere [Oxley *et al.*, 2012].

From these various studies we can conclude that the UKIAM can reproduce valid *total* concentrations and pollutant deposition rates, and that it compares well with other models. Evaluation of the source-apportionment of these totals is ongoing in order to better understand the both the uncertainties and the different representations of these totals by the various models discussed above.

FIGURE 6

Uncertainty

At a time when Integrated assessment modelling is increasingly providing the scientific basis for policy development in relation to air quality and climate change, scientists and modellers are facing a dilemma: *How can we effectively address uncertainty?* Whereas policy makers demand quantifications of uncertainty from these state-of-the-art models, the increasingly complex and inter-dependent scientific domains and spheres of human activity captured by the models means that scientists can rarely provide better than qualitative representations of uncertainty. To emphasise this problem a recent uncertainty review concluded that *"the greatest uncertainty is in quantification of the uncertainties themselves."* [EC4MACS, 2010; Amann *et al.*, 2011]. Moreover, uncertainty tends to be addressed in a fragmented way, either quantitatively or qualitatively, usually only in parts of the models (eg. emissions inventories; costs/benefits etc.), often ambiguously and confused with model sensitivities or scenario analyses, and not always adequately.

Current techniques for addressing uncertainty in the context of policy development include HAZard and OPerability studies (HAZOP), which can be used as a risk assessment technique to help identify areas of uncertainty, including assumptions and external factors that are not directly modelled, for example in negotiation of the Gothenburg Protocol [ApSimon *et al.*, 2002]. Other techniques use uncertainty matrices which can capture knowledge-related uncertainty [Walker *et al.*, 2003; Petersen, 2006], or Artificial Neural Networks which analyse a range of parameter values for multiple influences [Carnevale *et al.*, 2009]. Cullen & Frey (1999) provide an extensive handbook of probabilistic techniques for exposure assessment.

A variety of sensitivity studies have been carried out with the UKIAM in order to assess the impact upon concentrations and deposition rates resulting from the use of alternative representations of inputs (such as aerosol concentrations derived from the EMEP model as opposed to the FRAME model), different energy projections, and changes in emissions factors or activity levels [ApSimon & Oxley, 2010]. In relation to individual components of the UKIAM, others have documented uncertainties in relation to critical loads and natural ecosystems [Skeffington, 2006; Reinds & de Vries, 2010; http://cldm.defra.gov.uk/Uncertainties.htm], atmospheric chemistry and nitrogen deposition [Derwent, 1987; Sutton *et al.*, 2008], uncertainties in national emissions inventories [Passant, 2003; Bush *et al.*, 2010], road traffic forecasts [Jong *et al.*, 2007], or uncertainties that emerge from the integration of models of different spatial resolutions [Oxley *et al.*, 2011a].

As discussed by Briggs *et al*. (2009) in relation to epidemiological studies involving complex, integrated systems, uncertainties can arise in problem conceptualisation, analysis and the communication of results, concluding that the larger uncertainties may be associated with conceptualisation and communication than with the quantifiable results themselves. Recognising the complex inter-dependencies and relationships between different components of the UKIAM, along with their associated uncertainties, Oxley & ApSimon (2011) propose a conceptual framework which relates the wide variety and types of uncertainties encountered in integrated assessment modelling in a manner which is accessible to policy makers and will help them better understand the nature of the uncertainties and their practical implications.

Baseline Scenario (2020)

It is important to note that projections a decade or more into the future are based upon extensive modelling of expected changes over the given period. Projections cannot capture unexpected changes such as the impact of the recent recession on activity levels, although projections are routinely revised following such events so that they are subsequently taken into account. The UKIAM BAU2020 baseline reflects one such projection, whereas alternative projections have been reported under the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) to capture the effects of the 'credit crunch', and 'low carbon' projections to assess the impact of UNFCCC aspirations. The results presented below reflect the 'lower carbon' projection.

The UKIAM calculates a variety of tabulated and mapped outputs for each scenario. Maps of pollutant concentrations (NO_2, $PM_{2.5}$, secondary aerosols, etc.) and deposition are generated, the latter being used to calculate exceedances of critical loads in order to assess impacts on the natural environment. Exceedances are mapped and tabulated to describe the area of individual ecosystems showing exceedance, together with the overall magnitude of the exceedance (see Table 4). A selection of such maps are presented in Figure 7, describing the BAU2020 baseline.

FIGURE 7

TABLE 5

Pollutant concentrations, which describe the *background* air quality, provide input for the BRUTAL sub-model for road transport [Oxley *et al.*, 2009; 2012] to calculate roadside concentrations and metrics designed to address urban air quality (eg. km or road *at risk* of exceeding urban air quality limit values). Table 5 presents the main air quality metrics used for assessing urban air quality targets. Limit values are defined both as annual average and daily maximum concentrations with the model addressing the more stringent of the targets; since the model operates on an annual basis, the more stringent daily target for PM_{10} of a maximum of 35 exceedances of 50µg/m^3 is converted to a statistically derived annual average of 31.5µg/m^3 [AQEG, 2005]. Compared against exceedance calculations for 2010, the risk of exceedance is expected to be significantly reduced by 2020, assuming current legislation measures incorporated in the projections are implemented. Since the model is implemented at 1km^2 spatial resolution, it identifies the most polluted road in a grid cell and uses this as a proxy for all other roads in the same grid cell. The model may therefore be pessimistic, potentially over-estimating lengths of roads *at risk* of exceedance. The model also therefore calculates exceedance based upon a 10% increase in limit concentrations. This also highlights the sensitivity of the model relative to variations in the limit concentration (see Table 5), and suggests that between a third and half of exceedances of NO_2 are within 10% of the limit value, and, in the case of PM_{10}, exceedances in London all but disappear.

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TABLE 6

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The results presented here do not include comparisons with outputs from the GAINS model since this may be misleading because the models have been developed for different purposes. Whereas GAINS, at 50km^2 resolution, has been developed to address pollution abatement at the European-scale whilst maintaining a degree of equity between Member States, the UKIAM has been developed at 1km^2 and 5km^2 resolution in order to more precisely quantify impacts spatially within the UK. It has, for example, been shown elsewhere that exceedance of critical levels of NH_3 are significantly different when the resolution of deposition varies between 5km^2 and 1km^2 [Hallsworth *et al.*, 2007]. Oxley *et al.* (2011b) show that exceedances calculated based upon high resolution deposition patterns may suggest exceedances of critical loads which are several orders of magnitude greater than those suggested by European-scale models which provide deposition patterns at 50km^2 resolution.

In relation to air quality, GAINS quantifies health impacts (YOLLs) based upon background concentrations of $PM_{2.5}$ calculated at 50km^2 resolution [Amann *et al.*, 2011]. However, although developments are ongoing to address urban air quality more effectively within the framework of the GAINS model (see, for example, de Fouquet *et al.* (2011) and http://www.ec5macs.eu/), it cannot at this resolution adequately capture roadside air quality and quantify exceedance of air quality limit values.

However, alternative emissions scenarios evaluated using GAINS have been evaluated using the UKIAM in order to assess the sensitivity of impacts in the UK to changes in the transboundary contributions to deposition and concentrations of air pollutant in the UK (see Figure 5).

Potential for further reductions

Scenarios presented above include business-as-usual measures up to 2020, European reductions both to reflect the EU Thematic Strategy on Air Pollution (TSAP) and to achieve maximum realistic reductions (MRR). Scenarios have also combined these European reductions with additional UK measures to achieve maximum feasible reduction (MFR) for both industrial and agricultural emissions. The relative effects upon UK deposition budgets for SO_X, NO_X and NH_X of these increasingly stringent scenarios are highlighted in Figure 5. The effect of alternative definitions of European baseline 'current legislation' emissions (ie. PRIMES or National scenarios) upon the UK is negligible.

Further reductions beyond MFR are possible, although they may involve high costs and/or require a fundamental shift in approach to emissions reductions. Such measures may become necessary if targets agreed under revisions of the EU National Emissions Ceiling Directive or the Gothenburg Protocol prove difficult to achieve. A benefit of integrated assessment modelling is that such scenarios can be evaluated in relation to their potential benefits. Although the potential for significant further reductions in SO_2 emissions is small, in relation to NO_X:

- a widespread reduction in emissions from shipping is possible through introduction of Nitrogen Emissions Control Areas (NECA);
- further reductions in emissions from road transport are possible through vehicle downsizing and reducing overall demand for travel, widespread electrification or introduction of hydrogen fuel cell vehicles (see, for example, Oxley *et al.* (2012)); and
- a dramatic shift towards renewable energy production has the potential to further reduce emissions from small power stations and domestic combustion.

NH_3 emissions are currently dominated by agriculture, with possible abatement measures being counterbalanced by potentially increasing emissions from industrial sources, such as post-combustion CCS using amines [Tzanidakis, 2011]. Although further significant reduction of NH_3 emissions may be difficult to achieve, uncertainties in livestock projections resulting from changing demand, such as from reduced consumption of red meat, has the potential to shift the balance of livestock numbers and further reduce emissions in environmentally sensitive areas [Hasnain, 2009].

Conclusions

Integrated assessment models are used to support policy development in relation to air pollutants and greenhouse gases by providing integrated simulation tools able to produce quick and realistic representations of impacts without needing to re-run complex atmospheric dispersion models. In this paper we have described the multi-scale UK Integrated Assessment Model (UKIAM), how it captures UK emissions, handles atmospheric dispersion of pollutants, and the resultant impacts upon human health and ecosystems. Dynamically integrated with the European scale, the impacts of emissions projections and pollution abatement both in the UK and across Europe can be assessed simultaneously to provide information describing the socio-natural context for policy development in relation to air pollution and greenhouse gas emissions.

Evaluation of alternative abatement strategies analysed by UKIAM relies upon 5km resolution maps of deposition patterns (NO_x, SO_x and NH_x) and concentrations of secondary inorganic aerosols (NO_3, SO_4 and NH_4), 1km resolution maps of NO_x/NO_2 and $PM_{10/2.5}$, mapped and tabulated exceedance of ecosystem critical loads for eutrophication and acidification, and exceedance of air quality limit values.

The UKIAM has been applied to scenarios covering different energy projections [ApSimon & Oxley, 2010], road transport [Oxley *et al.*, 2012] and agriculture [Hasnain, 2009], and has been evaluated against other UK models as part of a model inter-comparison study carried out by Defra [Carslaw, 2011a; 2011b]. Results presented herein describe baseline projections to 2020 together with maximum feasible reductions from this baseline and speculative 'Beyond MFR' pollution abatement. Associated emissions reductions of air pollutants and greenhouse gases can be evaluated in relation to NECD targets, commitments under the Gothenburg Protocol, and aspirations towards reductions of CO_2 emissions [UNFCCC, 2010].

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Glossary

AAE	Average Accumulated Exceedance (kEq/ha/yr)
ADMS	ADMS is a pollution model for tackling air pollution problems in cities and towns, developed by Cambridge Environmental Research Consultants, http://www.cerc.co.uk/
ASAM	Abatement Strategies Assessment Model [ApSimon *et al.*, 1994; Warren & ApSimon 1999; 2000], Imperial College London
BAU	Business-As-Usual
BRUTAL	A road transport sub-model developed for the UKIAM [Oxley *et al.*, 2009; 2012].
CBED	Concentration Based Estimated Deposition [Smith *et al.,* 2000 ; Smith & Fowler, 2001]
CCS	Carbon Capture and Storage
CLE	Current Legislation
CLRTAP	Convention on Long-Range Transboundary Air Pollution, http://www.unece.org/env/lrtap/
CMAQ	Community Multiscale Air Quality modelling system, http://www.cmaq-model.org/
DECC	Department of Energy & Climate Change, http://www.decc.gov.uk/
Defra	Department of Environment, Food & Rural Affairs, http://www.defra.gov.uk/
DfT	Department for Transport, http://www.dft.gov.uk/
EC4MACS	European Consortium for Modelling of Air pollution and Climate Strategies, funded by the EU-LIFE Programme, Contract LIFE06/PREP/A/000006, http://www.ec4macs.eu/
EMEP	(1) Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (1984, Geneva Protocol) http://www.emep.int/ (2) Unified EMEP Eulerian model http://www.emep.int/UniDoc/index.html
FRAME	Fine Resolution Atmospheric Multi-species Exchange model [Fournier *et al.*, 2004]
GAINS	Greenhouse gas and Air pollution INteractions and Synergies; a development of the RAINS model to address the inter-relationships with effects of greenhouse gasses (GHG), http://www.iiasa.ac.at/rains/gains/
HGV/LGV	Heavy Goods Vehicle/Light Goods Vehicle
IIASA	International Institute for Applied Systems Analysis, Laxenburg, Austria http://www.iiasa.ac.at/
IAM	Integrated Assessment Model(ling)
iMOVE	integrated Model Of Vehicle Emissions [Valiantis, 2007]
LV	Air quality Limit Value specified by the EU Framework Directive 96/62/EC on ambient air quality, and 1st Daughter Directive (1999/30/EC) relating to NO_X, SO_2 and PM_{10}.
MARPOL	International Convention for the Prevention of Pollution from Ships, http://www.imo.org/
MFR/MRR	Maximum Feasible/Realistic Reduction
NAEI	National Atmospheric Emissions Inventory, http://www.naei.org.uk/
NEC	National Emissions Ceilings Directive (NECD) 2001/81/EC

NECA	Nitrogen Emissions Control Areas
NO_X	Nitrogen Oxides, mainly comprising NO and NO_2
PM_{10}	Airborne Particulate Matter less than 10 microns in diameter
$PM_{2.5}$	Airborne Particulate Matter less than 2.5 microns in diameter
PPM	(1) Primary Particulate Matter; (2) Primary Particulates Model [ApSimon *et al.*, 2001]
PRIMES	A partial equilibrium energy model proscribed by EU for use in policy impact assessments http://ec.europa.eu/environment/air/pollutants/models/primes.htm (see also www.ec4macs.eu)
PWM	Population Weighted Mean concentration (µg/m^3) of an air pollutant, calculated as the sum of all exposures divided by the total population
RAINS	Regional Acidification INformation System, http://www.iiasa.ac.at/~rains/ ; Regional Air pollution INformation and Simulation model (online), http://www.iiasa.ac.at/web-apps/tap/RainsWeb/
SECA	Sulphur Emissions Control Areas, applicable to shipping under the revised MARPOL Annex VI (www.imo.org)
SIA	Secondary Inorganic Aerosols (ie. NH_4, SO_4 and NO_3)
SNAP	Selected Nomenclature for Air Pollution (http://www.citepa.org/emissions/methodologie/)
SOA	Secondary Organic Aerosols
SRM	Source-Receptor Matrices calculated by atmospheric dispersion models (eg. FRAME or EMEP) and used by Integrated assessment models to define impact footprints of emissions sources
TFIAM	UN/ECE Task Force on Integrated Assessment Modelling http://www.unece.org/env/tfiam/
TRACK	TRajectory model with Atmospheric Chemical Kinetics [Lee *et al.*, 2000]
TSAP	EU Thematic Strategy on Air Pollution, COM(2005)446
UEP	The Updated Energy Projections (UEP) are published annually by the Department of Energy and Climate Change (DECC) to provide updated projections and analysis of energy use and carbon dioxide emissions in the UK
UKIAM	UK Integrated Assessment Model [Oxley *et al.*, 2003; and described herein], Imperial College London
UNECE	United Nations / Economic Cooperation in Europe (UN/ECE), http://www.unece.org/
UNFCCC	United Nations Framework Convention on Climate Change, http://unfccc.int/
VOC	Volatile Organic Compounds

References

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Hoglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F. & Winiwarter, W., 2011, Cost-effective control of air quality and greenhouse gases in Europe: modelling and policy applications, *Environmental Modelling & Software*, 26(12), 1489-1501, doi:10.1016/j.envsoft.2011.07.012

AMEC, 2009a, Multi-Pollutant Measures Database, Report to Defra, August 2009, AMEC Environment & Infrastructure UK, available from http://www.defra.gov.uk/environment/quality/air/airquality/publications/

AMEC, 2009b, Shipping emissions abatement measures review, Report to Defra, December 2009, AMEC Environment & Infrastructure UK

ApSimon, H., Amann, M., Åström, S. & Oxley, T., 2009, Synergies in addressing air quality and climate change, *Climate Policy* 9, 669-680

ApSimon, H.M., Gonzalez del Campo, T., Adams, H.S., 2001. Modelling long-range transport of primary particulate material over Europe. *Atmospheric Environment*, 35, 343–352.

ApSimon, H. & Oxley, T., 2010, Scientific Support for Defra in development of National and International Policy (SSNIP), Contract AQ0902, Final Report, Centre for Environmental Policy, Imperial College London, June 2010, http://uk-air.defra.gov.uk/library/

ApSimon, H., Warren, R. & Mediavilla-Sahagun, A., 2002, Applying Risk Assessment Techniques to Air Pollution Modelling & Abatement Strategies, pp189-199, in [Borrego & Sayers (eds), Air Pollution Modelling and Its Application XV, Kluwer Academic, New York, 2002, ISBN 978-0-306-47813-0]

ApSimon, H.M., Warren, R.F. & Wilson, J.J.N., 1994, The abatement strategies assessment model - ASAM: Applications to reductions of sulphur dioxide emissions across Europe, *Atmospheric Environment*, 28, 4, 649-663

AQEG (Air Quality Expert Group), 2005, Particulate Matter in the United Kingdom, Report to Defra by the Air Quality Expert Group, available from: http://uk-air.defra.gov.uk/library/

Bickel, P. & Friedrich, R. (eds.), 2005, ExternE - Externalities of Energy: Methodology 2005 Update, Report to the European Commission, http://www.externe.info/publications.html

Bush, T., Tsagatakis, I., Passant, N., Griffin, A. & B. Pearson, 2010, UK Emission Mapping Methodology 2007, National Atmospheric Emissions Inventory, September 2010, AEAT/ENV/R/2863

Briggs, D., Sabel, C. & Lee, K., 2009, Uncertainty in epidemiology and health risk and impact assessment, *Environ. Geochem. Health,* 31, 189-203, doi: 10.1007/s10653-008-9214-5

Carnevale, C., Finzi, G., Pisoni, E. & Volta, M., 2009, Neuro-fuzzy and neural network systems for air quality control, *Atmospheric Environment*,43, 4811-4821

Carruthers, D.J., McHugh, C.A., Williams, M., Johnson, K. & Jackson, M., 2010, The performance of ADMS-Urban for modelling long-term projections and short-term forecasts of urban air quality. Proceedings of the 13th International Conference on Harmonisation within Atmospheric Dispersion modelling for Regulatory Purposes, Paris, France, 1-4 June 2010

Carslaw, D.C., 2011a, Defra deposition model evaluation analysis – Phase 1, Report to Defra, Environmental Research Group, King's College London, 15th April 2011, http://uk-air.defra.gov.uk/reports/

Carslaw, D.C., 2011b, Defra urban model evaluation analysis – Phase 1, Report to Defra, Environmental Research Group, King's College London, 15th April 2011, http://uk-air.defra.gov.uk/reports/

Carslaw, D.C., and Beevers, S.D., 2005. Estimates of road vehicle primary NO_2 exhaust emission fractions using monitoring data in London. *Atmospheric Environment*, 39(2005): 167 - 177.

Chemel, C., Sokhi, R.S., Dore, A.J., Sutton, P., Vincent, K.J., Griffiths, S.J., Hayman, G.D., Wright, R., Baggaley, M., Hallsworth, S., Prain, H.D. & B.E.A. Fisher, 2011, Predictions of UK Regulated Power Station Contributions to Regional Air Pollution and Deposition: A Model Comparison Exercise. *Journal of Air & Waste Management Association* (in press)

Cullen, A.C. & Frey, H.C., 1999. Probabilistic Techniques in Exposure Assessment: A Handbook for Dealing with Variability and Uncertainty in Models and Inputs. Plenum Press, New York, USA.

Defra (Department for Environment, Food and Rural Affairs), 2001, National Ammonia Reduction and Strategies Evaluation System (NARSES), Project AM0101, 2001. http://www.defra.gov.uk/

Defra, 2010, Scientific Support for National and International Policy (SSNIP), Project AQ0902, http://www.defra.gov.uk/

Derwent, R. G., 1987, Treating uncertainty in models of the atmospheric chemistry of nitrogen compounds, *Atmospheric Environment*, 21(6), 1445-1454

Dore, A., Kryza, M., Hallsworth, S., Matejko, M., Vieno, M., Hall, J., van Oijen, M., Zhang, Y., Smith, R. & Sutton, M., 2009, Modelling the deposition and concentration of long range air pollutants, Final Report to Defra, Contract CPEA34

Dore, A.J., Vieno, M., Fournier, N., Weston, K.J., & M.A. Sutton, 2006, Development of a new wind rose for the British Isles using radiosonde data and application to an atmospheric transport model. *Quarterly Journal of the Royal Meteorological Society*, 132, 2769-2784

Dore, A. J.; Vieno, M.; Tang, Y. S.; Dragosits, U.; Dosio, A.; Weston, K. J.; Sutton, M. A., 2007, Modelling the atmospheric transport and deposition of sulphur and nitrogen over the United Kingdom and assessment of the influence of SO_2 emissions from international shipping. *Atmospheric Environment*, 41 (11), 2355-2367.

EC4MACS, 2010, Workshop on uncertainty treatment, IIASA, Laxenburg, 3-4 November 2010, www.ec4macs.eu

EDINA, 2009, Agricultural Census Data, ED*i*NA is a JISC National Data Centre at Edinburgh University Data Library http://edina.ac.uk/agcensus/

EMEP, 2010, Transboundary acidification, eutrophication and ground level ozone in Europe in 2008, EMEP Status Report 1/10, Joint MSC-W & CCC & CEIP Report, Norwegian Meteorological Institute, http://www.emep.int/ Erisman, J.W., Bleeker, A. and van Jaarsveld, J.A. (1998) Evaluation of ammonia emission abatement on the basis of measurements and model calculations. *Environmental Pollution,* 102, 269-274.

Fecht, D., 2011, Development and application of a simulated urban system for geographical studies of environmental health, PhD Thesis, St Mary's College, Imperial College London, February 2011

de Fouquet, C., Malherbe, L. & Ung, A., 2011, Geostatistical analysis of the temporal variability of ozone concentrations. Comparison between CHIMERE model and surface observations, *Atmospheric Environment*, 45, 3434-3446.

Fournier, N., A.J. Dore, M. Vieno, K.J. Weston, U. Dragosits & M.A. Sutton, 2004, Modelling the deposition of atmospheric oxidised nitrogen and sulphur to the United Kingdom using a multi-layer long-range transport model. *Atmospheric Environment*, 38(5), 683-694.

Fournier, N., K.J. Weston, A.J. Dore and M.A. Sutton, 2005, Modelling the wet deposition of reduced nitrogen over the British Isles using a Lagrangian multi-layer atmospheric transport model. *Quarterly Journal of the Royal Meteorological Society*, 131, 703-722.

Gonzales del Campo, T., 2003, Integrated Assessment of Abatement Strategies for Particulate Matter, PhD Thesis, Department of Environmental Science & Technology, Imperial College London, 2003

Hall, J. (ed.), 2003, Status of UK Critical Loads: Critical Loads Methods, Data and Maps. UK National Focal Centre, Centre for Ecology & Hydrology, February 2003, http://critloads.ceh.ac.uk/

Hall, J., Evans, C., Rowe, E. & Curtis, C., 2008, UK National Focal Centre report. In: Hettelingh, J.P., Posch, M., Slootweg, J. (eds.) Critical load, dynamic modelling and impact assessment in Europe: CCE Status Report 2008, Coordination Centre for Effects, Netherlands Environmental Assessment Agency, 211-216 (http://www.rivm.nl/cce)

Hallsworth, S., Sutton, M.A., Dore, A.J., Dragosits, U., Tang, Y.S. & M. Vieno, 2010, The role of indicator choice in quantifying the ammonia threat to the 'Natura 2000' network, *Environmental Science & Policy*, 13, 671-687, doi:10.1016/j.envsci.2010.09.010

Hasnain, N., 2009, A multi-criteria approach to environmental policy: a case study in agricultural ammonia emissions, PhD Thesis, Centre for Environmental Policy, Imperial College London

Holland, M. & Watkiss, P., 2002, Benefits Table Database: Estimates of the marginal external costs of air pollution in Europe [online]. Available from http://ec.europa.eu/environment/enveco/air/pdf/betaec02a.pdf Hordijk, L. & Amann, M., 2007. How science and policy combined to combat air pollution problems. *Environmental Policy & Law* 37 (4), 336–340.

Jong, G., Daly, A., Pieters, M., Miller, S., Plasmeijer, R. & Hofman, F., 2007, Uncertainty in traffic forecasts: literature review and new results for The Netherlands, *J. Transportation*, 34(4), 375-395

Lennartz-Walker, T., 2010, Modelling trends in Nitrogen Dioxide in the UK with the BRUTAL model, MSc Thesis, Centre for Environmental Policy, Imperial College London, September 2010

Metcalfe, S.E., Whyatt, J.D., Broughton, R., Derwent, R.G., Finnegan, D., Hall, J., Mineter, M., O'Donoghue, M. & Sutton, M.A., 2001, Developing the Hull Acid Rain Model: its validation and implications for policy makers, *Environmental Science & Policy*, 4(1), pp 25-37

Oxley, T. & ApSimon, H., 2007, Space, time and nesting Integrated Assessment Models, *Environmental Modelling & Software*, 22, 1732-1749

Oxley, T. & ApSimon, H., 2011, A conceptual framework for mapping uncertainty in integrated assessment, International Congress on Modelling & Simulation (MODSIM2011), Perth, Australia, 12-16 December 2011

Oxley, T., ApSimon, H., Dore, A., Sutton, M., Hall, J., Heywood, E., Gonzales del Campo, T., & Warren, R., 2003, The UK Integrated Assessment Model, UKIAM: A national scale approach to the analysis of strategies for abatement of atmospheric pollutants under the CLRTAP, *Integrated Assessment*, 4(4), 236-249

Oxley, T., ApSimon, H. & Valiantis, M., 2011a, Modelling national air quality strategy scenarios with UKIAM: uncertainties emerging from the integration of multiple spatial scales, *Int. J. Environment & Pollution*, 44, 54-61

Oxley, T., Elshkaki, A., Kwiatkowski, L., Castillo, A., Scarbrough, T. & ApSimon, H., 2012, Pollution abatement from road transport: cross-sectoral implications, climate co-benefits and behavioural change, *Environmental Science & Policy* (in press), doi:10.1016/j.envsci.2012.01.004

Oxley, T., Hall, J. & ApSimon, H., 2011b, Spatialities and temporalities of metrics calculated by Integrated Assessment Models: Exceedance of ecosystem-specific Critical Loads, International Congress on Modelling & Simulation (MODSIM2011), Perth, Australia, 12-16 December 2011

Oxley, T., Valiantis, M., Elshkaki, A. & ApSimon, H., 2009, Background, Road and Urban Transport modelling of Air quality Limit values (the BRUTAL model). *Environmental Modelling & Software*, 24, 1036-1050

Page, T., J.D. Whyatt, K.J. Beven & S.E. Metcalfe, 2004, Uncertainty in modelled estimates of acid deposition across Wales: A GLUE approach. *Atmospheric Environment*, 38, 2079-2090.

Passant, N. R., 2003, Estimation of uncertainties in the NAEI, Report to Defra, AEAT/ENV/R/1039/Issue1

Petersen, A. C., 2006, A philosophical study of computer-simulation uncertainties and their role in climate science and policy advice, PhD Thesis, Antwerpen, ISBN 978 90 5589 280 8

Pope, C.A., Ezzati, M. & Dockery, D.W., 2009, Fine-Particulate Air Pollution and Life Expectancy in the United States, *New England Journal of Medicine*, 360(4), 376-386, doi: 10.1056/NEJMsa0805646

Reinds, G. & de Vries, W., 2010, Uncertainties in critical loads and target loads of sulphur and nitrogen for European forests: analysis and quantification, *Science of the Total Environment*, 408(8), 1960-1970

RoTAP, 2012, Review of Transboundary Air Pollution: Acidification, Eutrophication, Ground Level Ozone and Heavy Metals in the UK. http://www.rotap.ceh.ac.uk

Skeffington, R. A., 2006, Quantifying uncertainty in critical loads: literature review, *Water, Air & Soil Pollution*, 169, 3-24

Simpson, D., Fagerli, H., Jonson, J., Tsyro, S., Wind, P., Tuovinen, J., 2003. Unified EMEP model description, EMEP status report part I. http://www.emep.int/UniDoc/

Smith, R.I. & Fowler, D., 2001, Uncertainty in wet deposition of sulphur. *Water, Air and Soil Pollution: Focus* **1**: 341-354.

Smith, R.I., Fowler, D., Sutton, M.A., Flechard, C. & Coyle, M., 2000, Regional estimation of pollutant gas deposition in the UK: model description, sensitivity analyses and outputs, *Atmospheric Environment,* 34, 3757-3777.

Stedman, J.R., Kent , A.J., Grice, S., Bush, T.J. and Derwent, R.G., 2007, A consistent method for modelling PM_{10} and $PM_{2.5}$ concentrations across the United Kingdom in 2004 for air quality assessment. *Atmospheric Environment*, 41, pp161-172.

Sutton, M., Simpson, D., Levy, P., Smith, R., Reis, S., van Oijen, M. & de Vries, W., 2008, Uncertainties in the relationship between atmospheric nitrogen deposition and forest carbon sequestration, *Global Change Biology*, 14, 2057-2063

Tsyro, S. G., 2005, To what extent can aerosol water explain the discrepancy between model calculated and gravimetric PM_{10} and $PM_{2.5}$?, *Atmos. Chem Phys*., 5, pp 515-532

Tzanidakis, K., 2011, Environmental and human health impacts of Carbon Capture and Storage in the UK, MSc Thesis, Centre for Environmental Policy, Imperial College London, September 2011

UNECE, 1999. The 1999 Gothenburg Protocol to abate acidification, eutrophication and ground-level ozone, United Nations/Economic Cooperation in Europe. http://www.unece.org/env/lrtap/.

UNECE, 2011, Options for revising the annexes to the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone: annex II, Report by the chair of the Task Force on Integrated Assessment Modelling (TFIAM) to the Executive Body of the Convention on Long-Range Transboundary Air Pollution and the Working Group on Strategies and Review, ECE/EB.AIR/GE.1/2011/4–ECE/EB.AIR/WG.5/2011/18, http://www.unece.org/

UNFCCC, 2010, Report of the Conference of the Parties on its fifteenth session (COP15), Copenhagen, 7-19 December, 2009, FCCC/CP/2009/11/Add.1, 30 March 2010, http://www.unfccc.int/

Valiantis, M., Oxley, T. & ApSimon, H., 2007, Assessing alternative transport scenarios in relation to the UK air quality strategy. In: 6th International Conference on Urban Air Quality, Cyprus, 27–29 March 2007.

Vardoulakis, S., Valiantis, M., Milner, J., & ApSimon, H., 2007, Operational air pollution modelling in the UK – street canyon applications and challenges. *Atmospheric Environment* 41 (22), 4622–4637.

Vieno, M., Dore, A.J., Bealey, W.J., Stevenson D.S. & M.A. Sutton, 2010, The importance of source configuration in quantifying footprints of regional atmospheric sulphur deposition. *Science of the Total Environment*, 408(4), 985-995

Vieno, M., Dore, A. J., Stevenson, D. S., Doherty, R., Heal, M. R., Reis, S., Hallsworth, S., Tarrason, L., Wind, P., Fowler, D., Simpson, D. & M. A. Sutton, 2009, Modelling surface ozone during the 2003 heat wave in the UK, *Atmospheric Chemistry & Physics Discussions* (ACPD), 9, 19509–19544

Wagner, A., 2010, NECD Submission: 2010 Emission Projections, Report to Defra by AEA Technology, http://uk-air.defra.gov.uk/reports/cat07/1012161052_2010_NECD_Submission_Report.pdf

Wagner, F., Amann, M., Bertok, I., Cofala, J., Heyes, C., Klimont, Z., Rafaj, P. & Schöpp, W., 2010, Baseline emission projections and further cost-effective reductions of Air Pollution Impacts in Europe – A 2010 Perspective, NEC Scenario Analysis Report Nr. 7, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Walker, W. E., Harremoës, P., Rotmans, J., Van der Sluijs, J. P., van Asselt, M. B. A., Janssen, P. H. M. & Krayer von Krauss, M. P., 2003, Defining Uncertainty: A conceptual basis for uncertainty management in model-based decision support, *Integrated Assessment*, 4(1), 5-17

Warren, R. & ApSimon, H., 1999, Uncertainties in integrated assessment modelling of abatement strategies: illustrations with the ASAM model, *Environmental Science & Policy*, 2, 6, 439-456

Warren, R. & ApSimon, H., 2000, Integrated assessment of sulphur dioxide reduction schemes: Robustness studies, choice of environmental targets and country roles, *Journal of Environmental Management*, 59, 1, 3-20

Williams, M., Barrowcliffe, R., Laxen, D. & Monks, P. (Eds), 2011, Review of air quality modelling in Defra, A report by the Air Quality Modelling Review Steering Group, 7 April 2011

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Figure 6 – Comparison of concentrations modelled by UKIAM/BRUTAL against measurements from the London Air Quality Network (LAQN) for 2010, from Carslaw (2011b). Agreement is good for background and suburban sites, although kerbside measurements tend to be underestimated owing to the relatively coarse ($1km^2$) resolution of the model (See Oxley *et al.*, 2009 for details).

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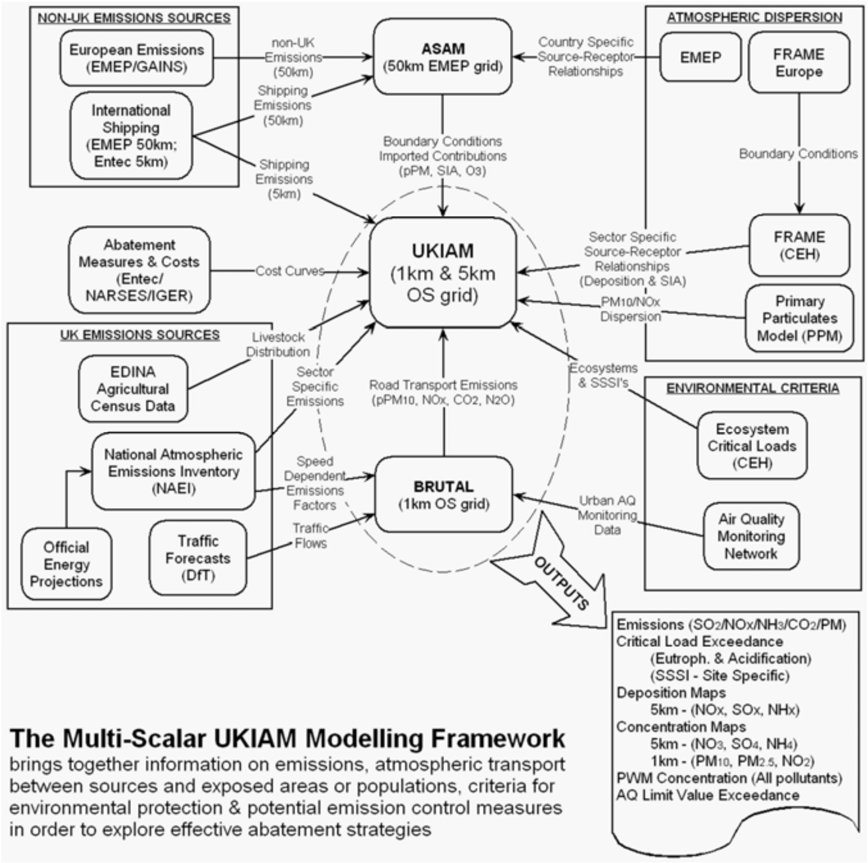

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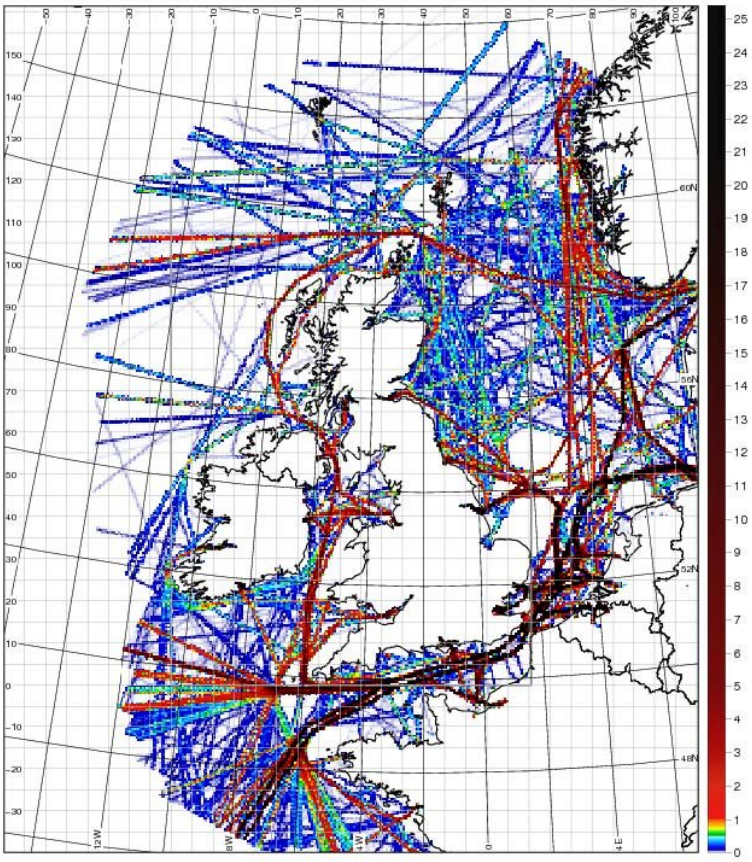

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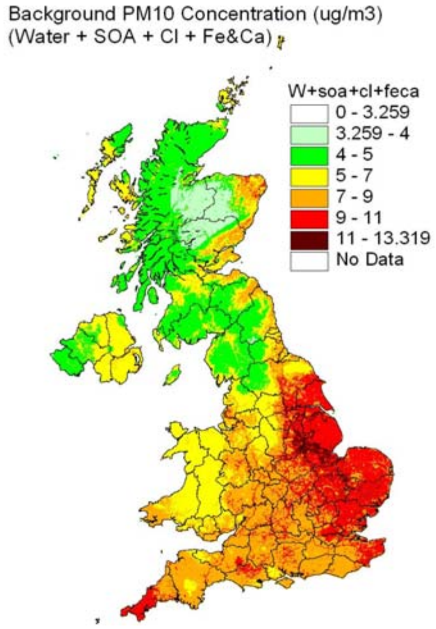

PWM Concentrations (µg/m^3)
Background PM

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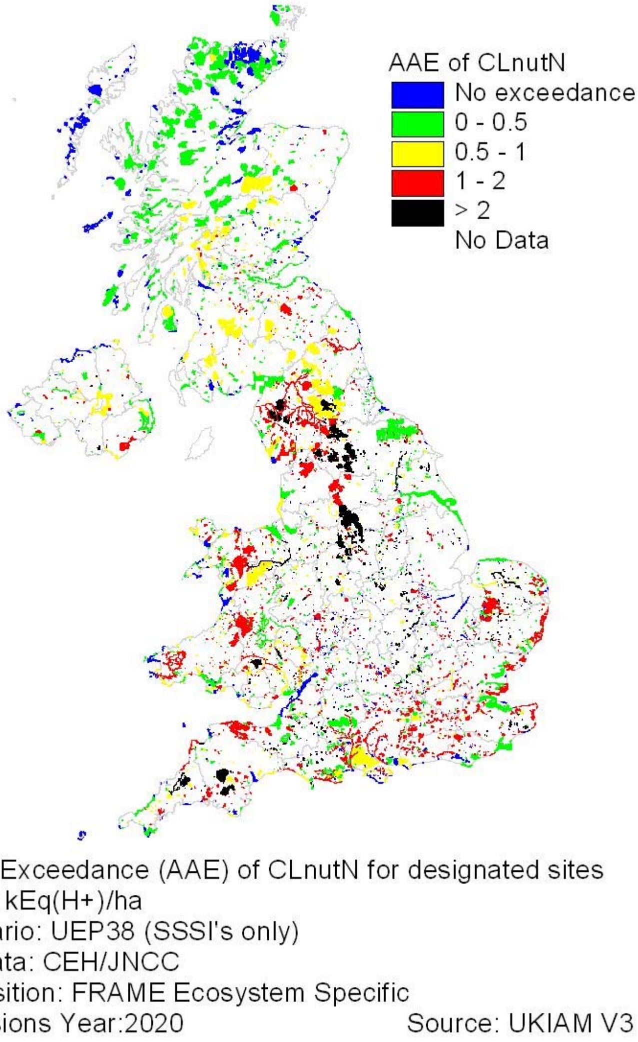

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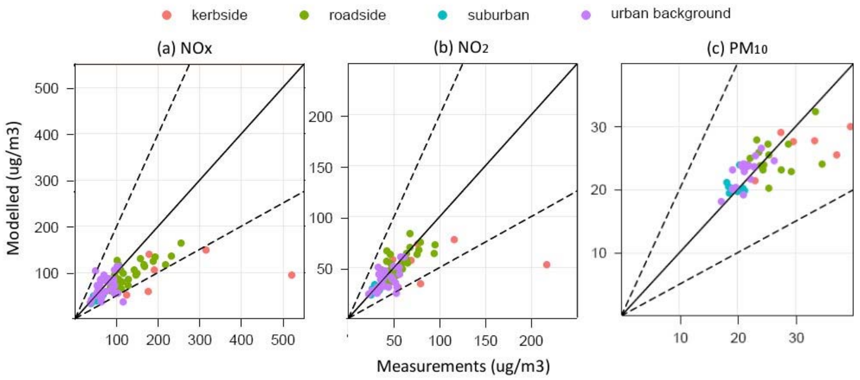

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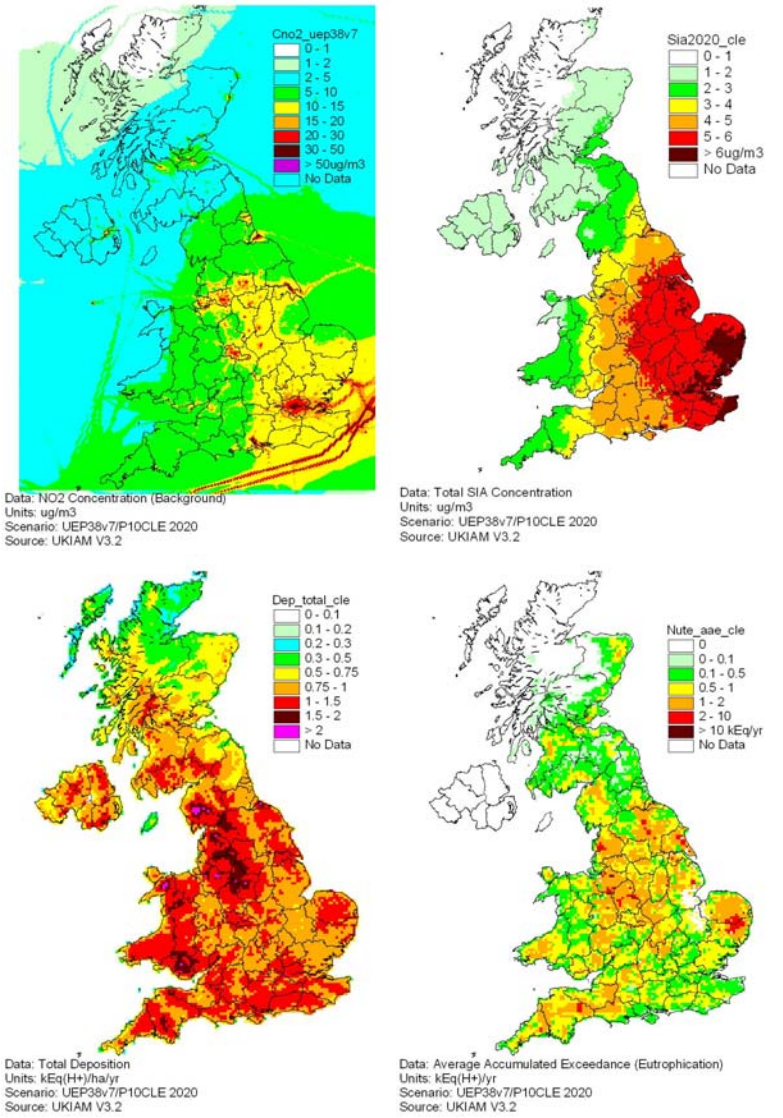

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Table 1 – Summary of baseline emissions by source for the UKIAM, excluding shipping. EU27 emissions are based upon National projections

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Table 1 – Summary of baseline emissions by source for the UKIAM, excluding shipping. EU27 emissions are based upon National projections

Emissions (Tons)					
2010	PM_{10}	$PM_{2.5}$	NH_3(1)	SO_2	NO_X
Power	3,890	2,571	0	134,459	279,866
Combustion(2)	17,007	10,330	0	18,973	109,251
Industry	42,871	24,560	38,797	180,651	229,079
Roads	25,105	20,084	0	578	338,915
Off-road	9,424	7,444	0	11,060	152,900
Agric./Nat	15,687	6,709	268,587	0	487
Tot. UK(3)	113,983	71,699	307,384	345,721	1,110,498
EU27	1,864,970	1,301,060	3,760,490	3,958,660	8,725,500
2020	PM_{10}	$PM_{2.5}$	NH_3(1)	SO_2	NO_X
Power	5,841	3,674	0	62,153	114,789
Combustion(2)	15,303	7,631	0	5,441	95,728
Industry	35,154	20,356	38,797	156,596	194,218
Roads	13,188	8,109	0	2,269	129,278
Off-road	4,611	3,558	0	3,364	78,728
Agric./Nat	16,565	5,006	268,587	0	644
Tot UK(3)	90,663	48,334	307,384	229,823	613,386
EU27	1,672,060	1,094,700	3,733,590	2,894,480	5,767,480

NOTES:

(1) UK NH_3 emissions remain static at BAUIII (2020) conditions

(2) Includes both public and domestic combustion (SNAP02)

(3) No shipping emissions are included here

Table 2 – Summary of applicability's and efficiencies of abatement measures for the main industrial sources based upon review of the multi-pollutant measures database [AMEC, 2009a]; measures shown in italics represent alternative, as opposed to additional, measures. Although none of the measures shown affect NH_3 emissions, this pollutant must remain included since measures such as post-combustion Carbon Capture & Storage (CCS) technologies can significantly influence NH_3 emissions [Tzanidakis, 2011]

				Efficiency (%) of Measure				
Source Name	**Measure**	**% Applicability**	**% of source by fuel type**	**NH_3**	**SO_2**	**NO_X**	**PM_{10}**	**$PM_{2.5}$**
Cement	SNCR	100	100			70		
Cement	Wet Scrubbing	100	100		90			
Cement	Dry Absorbant	100	100		70			
Sinter	Fabric or metal mesh filter	100	100				95	95
Sinter	*Fabric filter with pre-inject.*	*100*	*100*		*40*		*95*	*95*
Sinter	*Partial waste gas recycle*	*100*	*100*		*20*	*45*	*60*	*60*
Sinter	*SCR*	*100*	*100*			*90*		
Iron & Steel	SCR	90	100			80		
Iron & Steel	ESP	90	100				95	95
Iron & Steel	Fabric Filter	90	100				95	95
Refineries	Switch fuel oil to Nat Gas	100	61.20		100		100	100
Refineries	*FGD (Fuel Oil)*	*100*	*61.20*		*95*		*50*	*50*
Refineries	FGD (Petroleum Coke)	100	38.80		95		50	50
Refineries	SCR	100	100			85		
Refineries	*SNCR*	*100*	*100*			*70*		
Autogenerators	Low S coal	100	100		50			
Autogenerators	*FGD (coal)*	*100*	*100*		*90*		*50*	*50*
Autogenerators	SCR (coal) - Power Plants	100	27.37			80		
Autogenerators	Gas - Combustion Mod.	85	72.63			50		
Autogenerators	*Gas - Comb Mod + SCR*	*85*	*72.63*			*77*		
Other Ind Comb	Low S coal	100	28.65		50			
Other Ind Comb	Low S coke	100	34.78		50			
Other Ind Comb	Low S fuel oil	100	27.38		50			
Other Ind Comb	Comb. Mod. (85% of plant)	85	92.75			50		
Other Ind Comb	*SNCR*	*85*	*92.75*			*70*		
Other Ind Comb	*Comb. Mod. + SCR*	*85*	*92.75*			*80*		
Power Stations	***Major Point Sources handled individually - dependent upon fuel mix and CCS***							
Road Transport	***Measures handled by the BRUTAL model (see Oxley et al., 2012)***							
Agric. NH_3	***Measures remain in form of cost-curve due to relationships between measures***							

Pollutant	Impact	Model	Type	Resolution	Comments
NO_X	NO_3 concentration ; Oxidised N deposition	FRAME	Lagrangian	5km	Includes cross-pollutant chemistry
NH_3	NH_4 concentration ; Reduced N deposition				
SO_2	SO_4 concentration ; Sulphur deposition				
NO_X	NO_2 concentration	UKIAM	Gaussian	1km	Non-road sources
		BRUTAL		1km/Roadside	Road transport
PM_{10}	PM_{10} concentration	UKIAM		1km	Non-road sources
		BRUTAL		1km/Roadside	Road transport
$PM_{2.5}$	$PM_{2.5}$ concentration	UKIAM		1km	Proportion of PM_{10} as $PM_{2.5}$ by source
CO_2/N_2O CH_4	Emissions only	UKIAM	n/a	5km	No dispersion
		BRUTAL		1km	Road trans.; no dispersion
O_3	O_3 conc; AOT; SOMO35	EMEP	Eulerian	50km	Data from GAINS model

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Broad_Habitat	Habitat Area (km^2)	Exceeded Area (km^2)	Percentage Area Exceeded	Accumulated Exceedance (kEq/year)
Acidity exceedances for the United Kingdom				
Acid grassland	15,334	9,644	62.89	639,453
Calcareous grassland	1,808	1.26	0.07	70.16
Dwarf shrub heath	24,703	4,247	17.19	187,240
Bog	5,463	1,823	33.37	125,333
Montane	3,054	1,474	48.28	35,100
Coniferous woodland (managed)	8,377	3,058	36.5	143,940
Deciduous woodland (managed)	7,452	2,881	38.66	179,664
Unmanaged woods	4,011	915.48	22.83	45,557
Freshwaters	3,482	234.5	6.74	12,474
All habitats	73,683	24,278	32.95	1,368,831
Nutrient nitrogen exceedances for the United Kingdom				
Acid grassland	15,241	6,980	45.8	273,616
Calcareous grassland	3,577	2,325	65	76,380
Dwarf shrub heath	24,820	4,698	18.93	180,373
Bog	5,541	1,814	32.73	111,210
Montane	3,129	2,315	73.99	38,309
Coniferous woodland (managed)	8,385	6,274	74.82	390,620
Broadleaved woodland (managed)	7,482	7,073	94.53	640,687
Unmanaged woods (ground flora)	3,296	2,776	84.23	228,193
Atlantic oak (epiphytic lichens)	822.04	498.81	60.68	37,221
Supralittoral sediment	2,128	545.76	25.65	11,994
All habitats	74,422	35,300	47.43	1,988,603

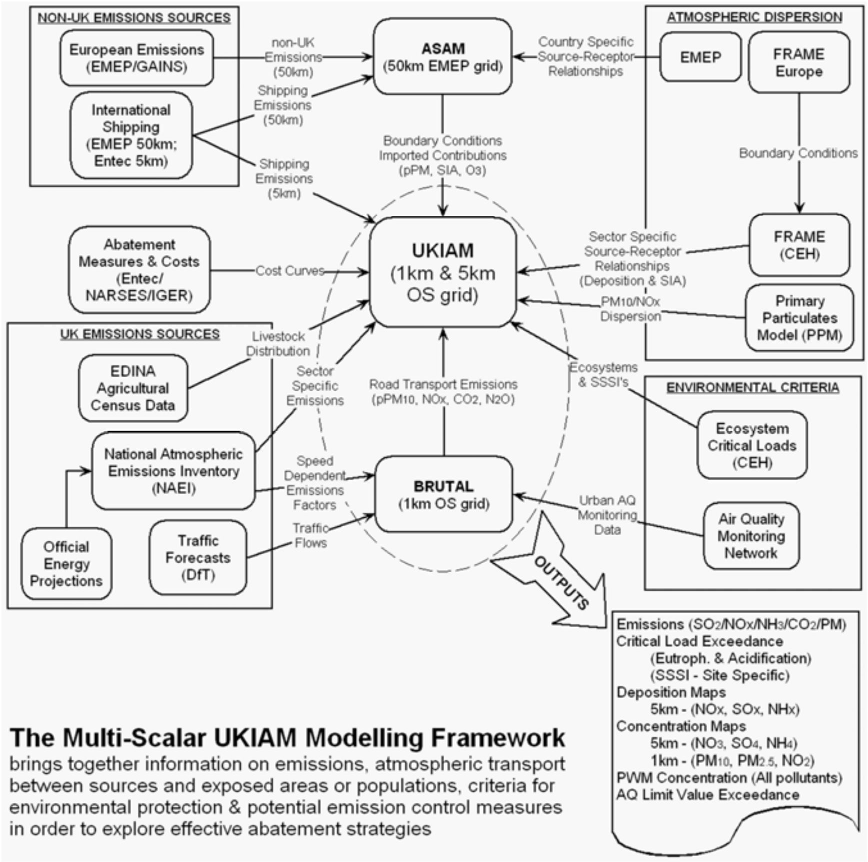
Table 5 - Summary of AQ metrics calculated by the BRUTAL sub-model for road transport. Exceedances are shown for London only since national figures may be distorted by apparent exceedances in rural areas (such as motorway intersections) where limit values are not applicable.

		Road Transport Emissions (kT/yr)	**Population Weighted Mean Conc. ($\mu g/m^3$)**		**km *at risk* of exceeding AQ Limit Value**	
AQ Pollutant	**Year**		**UK**	**London**	**Limit Value* London**	**LV+10% London**
NO_2	**2010**	323.558	16.916	31.391	1525	1151
	2020	124.356	9.364	18.114	90	
PM_{10}	**2010**	23.328	15.786	20.672	33	3
	2020	15.127	13.726	17.610	2	

** Limit Values: NO_2=40µg/m^3; PM_{10}=31.5µg/m^3*

RERUN TO REMAIN IN TUNE WITH MIP2? Also need +10% results for 2020 scenario

FIGURES (Black & White):



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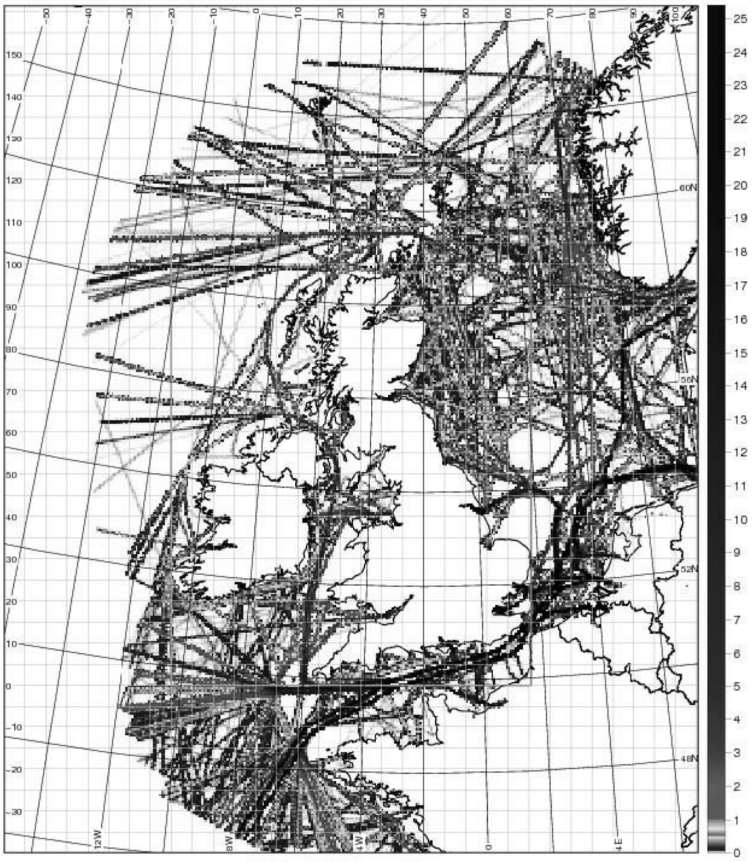

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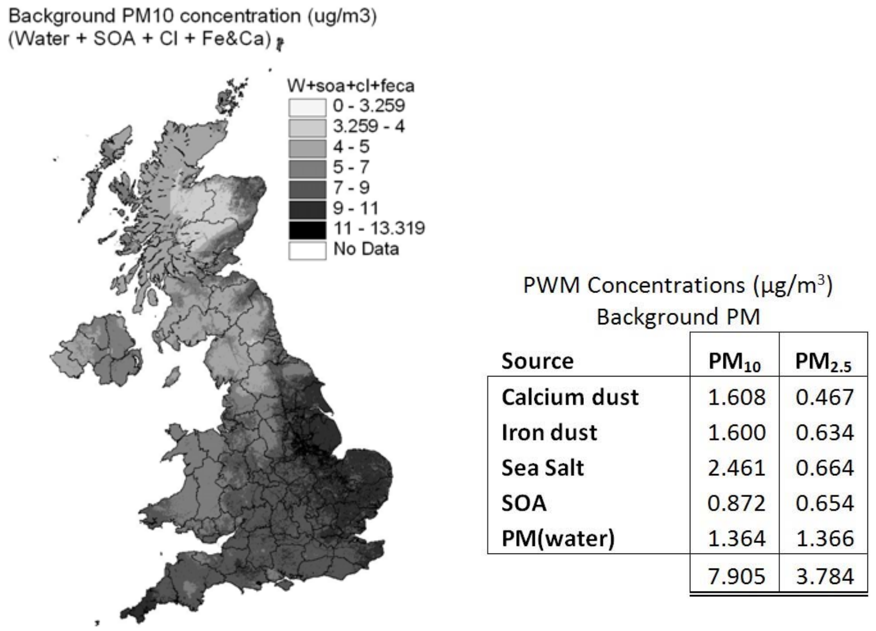

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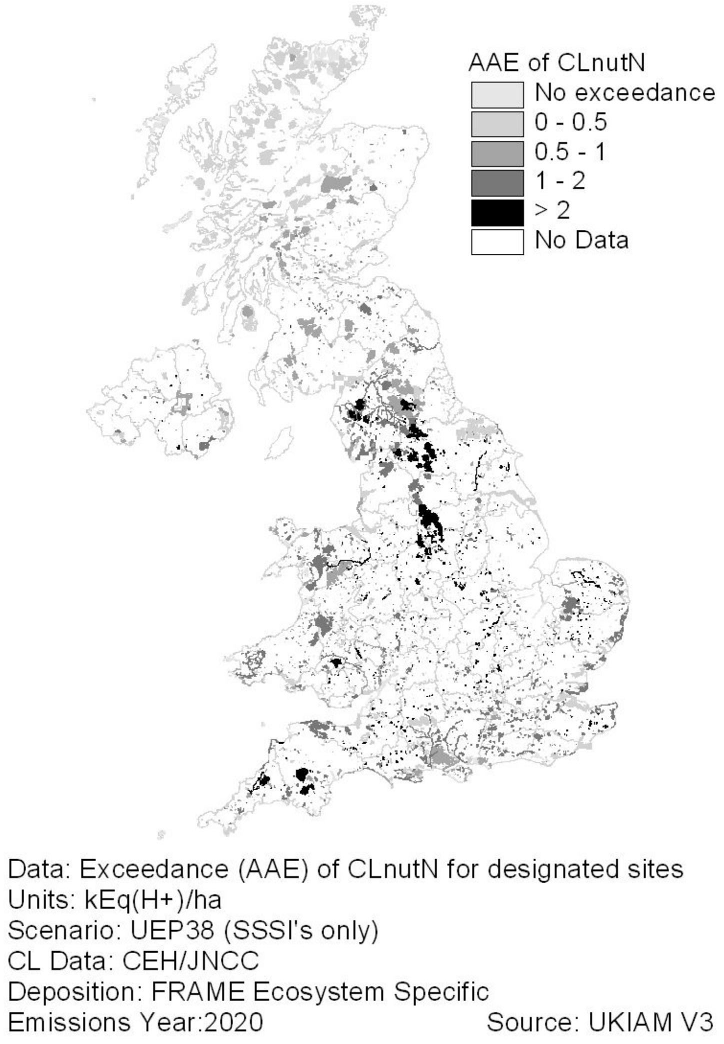

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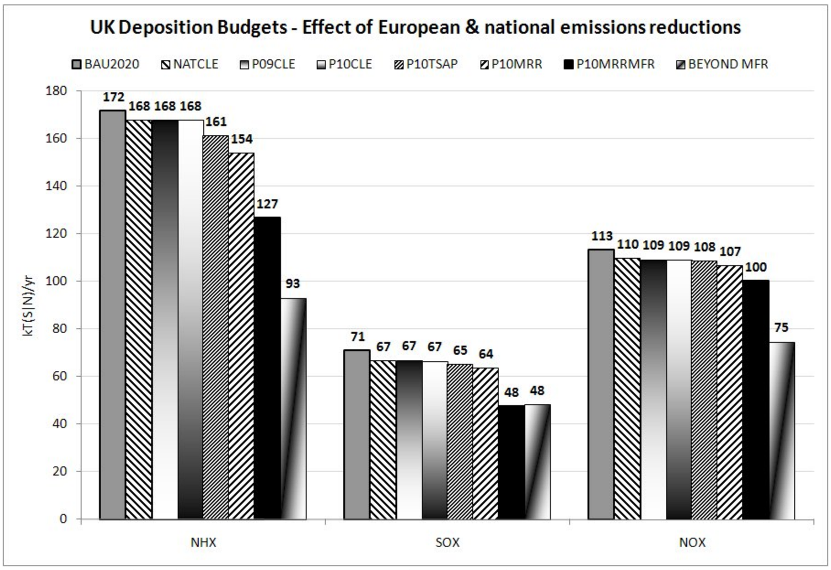

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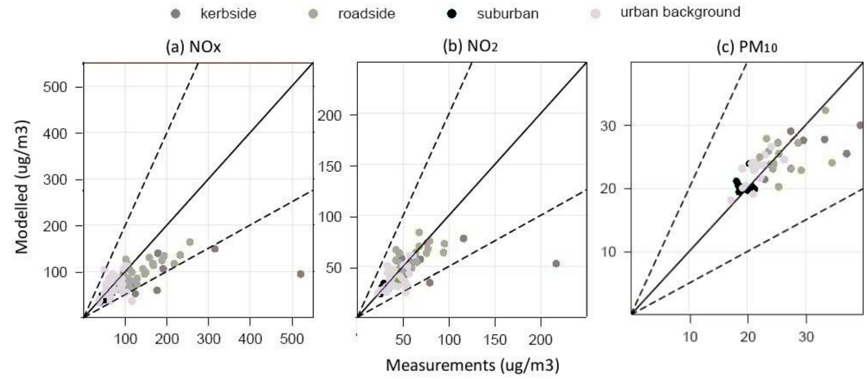

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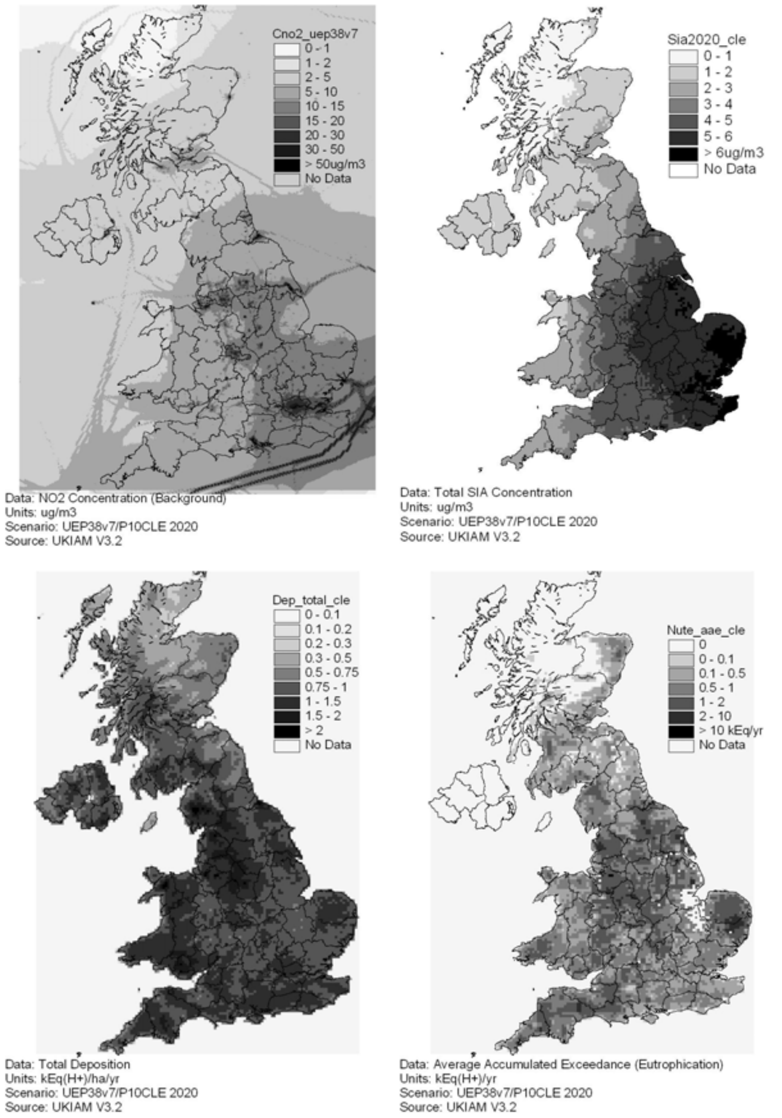

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