A framework for UK research and evidence needs relating to air pollution impacts on ecosystems

Inter-agency Air Pollution Group
(Joint Nature Conservation Committee, Natural England, Natural Resources Wales, Northern Ireland Environment Agency and Scottish Natural Heritage)

Version 1, published March 2015

For further information on air pollution issues, visit http://jncc.defra.gov.uk/page-1426

A framework for UK research and evidence needs relating to air pollution impacts on ecosystems

1. Introduction

1.1. Purpose of the *Framework*

The '*Framework for UK research and evidence needs relating to air pollution impacts on ecosystems*' has been produced by the Inter-agency Air pollution Group (IAPG), which consists of representatives from the Statutory Nature Conservation Bodies (SNCBs[1]). The approach taken by the group to develop the *Framework* has been to assess the current understanding of the impacts of air pollution on biodiversity, and to identify the main evidence and/or research gaps in the context of relevant policies.

The purpose of the document is to provide a framework for UK research and evidence needs relating to air pollution impacts on ecosystems. The *Framework* is aimed principally at informing the direction of future research of the SNCBs, much of which is likely to be undertaken in collaboration via the IAPG. It is therefore targeted at specific areas/questions which are a priority to help the SNCBs deliver their functions. However, it also includes evidence and research areas which are broader than the SNCBs' direct remit where these are traditionally funded by other bodies, but which the SNCBs depend on to interpret evidence.

The *Framework* is designed to be shared and to help inform the work of others with similar interests and responsibilities (e.g. Government departments and Devolved Administrations, environment agencies, research councils, universities, and industry). It aims to provide a structure to promote discussion on establishing agreed research priorities. Thus the *Framework* is intended to inform thinking on future needs and does not, at this stage, include commitments. It will be used by the SNCBs when working with partners to identify and prioritise evidence needs; for example, JNCC and Natural England will use the information in the *Framework* to support their input into the development of the Defra Network Evidence Action Plans (NEAPs). It is through such further dialogue that priorities will be agreed, and therefore the evidence gaps identified in the *Framework* have not been prioritised.

As a follow-up to the *Framework*, the IAPG will produce a 'next steps' programme. This will explain how the group will work with others to examine priorities, timescales, and opportunities for collaboration, as well as funding opportunities, in order to then develop the detail of specific projects. The IAPG relies heavily on the work of others, and part of the next steps process will be to identify who is best placed to take forward the research outlined in the *Framework*, and to establish the IAPG's role. Alongside this, efforts will be required to reinforce and renew communication of the *Framework* and the next steps process with a range of stakeholders.

1.2. Background

Air pollution remains a significant risk to human health and the natural environment. In 2014, the World Health Organisation described air pollution as the world's largest single environmental cause of mortality, attributable for approximately seven million deaths in 2012 (OECD 2012); in Europe, poor air quality is responsible for 400,000 deaths per year (EEA

[1] Natural England, Natural Resources Wales, Northern Ireland Environment Agency, Scottish Natural Heritage and the Joint Nature Conservation Committee.

2014). In 2010, the UK Environment Audit Committee (EAC) reported that many parts of the UK were continuing to breach mandatory targets for nitrogen dioxide and particulate matter (EAC 2013), and that air pollution in the UK was a major threat to human health and the natural environment (EAC 2013). It concluded that air pollution costs the UK economy as much as the health damage caused by obesity and smoking (EAC 2013). This equates to an annual cost of £16 billion, and reduces life expectancy by about six months (EAC 2013).

Air pollution has also caused widespread changes to species distribution and to the quality of natural and semi-natural habitats in the UK (Emmett *et al* 2011), and is a threat to the Conservation Status of many habitats listed under the Habitats Directive. The third UK Habitats Directive report, published in 2013[2], advised that, out of a total of 77 Annex I habitats, 34 had air pollution attributed as a high pressure and a high threat. In addition, data used to produce the UK Biodiversity Indicator on air pollution demonstrates that, at present, 65% of the area of sensitive habitat in the UK exceeds critical loads for nitrogen deposition (eutrophication)[3]. This is predicted to reduce only slightly by 2020 (ROTAP 2012) in response to existing measures. Consequently, additional measures are required to protect habitats from air pollution and to restore areas of habitats that are currently impacted.

There has been some physiochemical recovery from acidification of soils and freshwaters in the UK as a consequence of decreasing emissions of sulphur dioxide. However, biological recovery in freshwaters remains poorer than expected. In addition, acid deposition critical load exceedance continues, driven mainly by nitrogen deposition. Ozone also remains a pollutant of concern, with critical levels for ozone widely exceeded, and evidence that background concentrations are slowly increasing across the northern hemisphere (ROTAP 2012).

1.3. Developing a shared framework through the IAPG

The SNCBs co-ordinate their involvement in air pollution issues through the IAPG. Through this group they share issues and experiences to identify information gaps and to target priorities for collaborative work. This enables co-ordination of the provision of information and advice to Defra and the Devolved Administrations, together with provision of an evidence base to inform the country SNCBs' advice to the environment agencies and local planning authorities.

The main emphasis of the IAPG's work has been targeted at gathering evidence concerning the impacts of air pollution on ecosystems, which has focussed on atmospheric reactive nitrogen pollutants[4]. There continues to be a need to reinforce and renew this evidence base, whilst there is also a growing focus on measures, and their delivery mechanisms, to reduce impacts of air pollution on sensitive sites and the wider countryside.

The research needs identified in this *Framework* are centred on three high-level themes, which identify recommendations for areas of future evidence/research:

- ecosystem responses to changes in air pollution;
- assessing and reporting air pollution impacts; and
- measures and 'remedies' for air pollution.

[2] http://jncc.defra.gov.uk/page-6387
[3] UK Biodiversity Indicators in Your Pocket: http://jncc.defra.gov.uk/page-4245
[4] Reactive nitrogen – a term used to describe forms of nitrogen useable by plants and animals, for example ammonia, nitrates and nitric acid. Excess reactive nitrogen can lead to eutrophication of terrestrial and freshwater ecosystems.

This approach is supported by a contextual link to the relevant policy drivers. The document is structured to reflect the main interests and statutory responsibilities of the SNCBs, but acknowledges that some of the evidence to support the work has its main remit with other departments or organisations.

The *Framework* will be updated as new information arises and will be more systematically reviewed every 2–3 years.

2. Policy context

Air pollution policy in the UK is governed by international, European and UK agreements, commitments, policies and legislation. In addition, a range of other policy areas, including water, agriculture, energy, transport and climate change also influence emissions of air pollutants; there is a growing awareness of the need to integrate these policy areas.

Over the past few decades there have been a number of international and European-level agreements and initiatives to address air pollution, such as the Convention on Long Range Transboundary Air Pollution (CLRTAP) and its protocols. At a European scale, the Gothenburg Protocol (amended 2012), the Air Quality Directive, and the Industrial Emissions Directive are key drivers. In addition, a new air quality package was published by the European Commission in 2013. This included proposals for a revision of the National Emissions Ceilings Directive (NECD), which will set new ceilings for air pollutants, for 2030, and be expanded to include fine particulate matter ($PM_{2.5}$) and methane. The proposed revision to the NECD also includes a range of measures that Member States can adopt to reduce NH_3 emissions, and provisions for monitoring the impacts of air pollution on ecosystems.

Similarly, a range of policies and initiatives exist at various scales to protect and enhance biodiversity, which include targets or recommendations for reducing air pollution. At a global scale, the Strategic Plan[5] of the Convention on Biological Diversity (CBD), published in 2010, includes the target: “by 2020, pollution, including from excess nutrients, has been brought to levels that are not detrimental to ecosystem function and biodiversity”.

The European Biodiversity Strategy and the country biodiversity strategies in the UK also set targets or outcomes for biodiversity and ecosystem services which provide a driver for the reduction of air pollution impacts on ecosystems. These strategies sit alongside the provisions of other specific legislation such as the Habitats Directive and domestic legislation for the protection of Areas/Sites of Special Scientific Interest (A/SSSIs).

At a UK level, the 2013 UK Biodiversity Framework implementation plan[6] includes the following interim milestones for air pollution:

- Mainstream the impacts of air pollutants on biodiversity into wider air pollution work and policy evaluation. In 2013, summarise the implications of air pollution impacts for biodiversity commitments (such as the Habitats Directive) and evaluate effectiveness of emission reductions to inform UK position on the revision to the National Emission Ceilings Directive.
- By 2015, have established methods to provide future evidence of impacts (and recovery) via broad-scale vegetation surveillance.
- By 2015, identify ‘remedies/actions’ feasible to reduce pressure from air pollution on protected sites and to work across countries to share best practice for implementation.

[5] https://www.cbd.int/sp/
[6] http://jncc.defra.gov.uk/pdf/UKBioFwk_ImpPlan_November2013.pdf

- By 2015, establish methods to assess air pollution policy impacts on ecosystem services and provide valuation.

As the evidence base of air pollution impacts on biodiversity has increased, there has been an increasing focus on identifying measures and delivery mechanisms to minimise the impacts and to optimise potential co-benefits with other policy areas.

3. Current areas of work

The historical focus of the SNCBs has been on building on the evidence base to support and demonstrate the impacts of air pollution on biodiversity. The current focus includes continuing to demonstrate the impacts to support this evidence base, as well as developing methodologies to attribute and report air pollution impacts in the context of policy commitments, and to understand the future prospects of habitats in a changing pollution environment. At the same time there is an increasing focus on identifying and implementing measures to reduce or ameliorate the impacts of nitrogen deposition.

3.1. SNCBs' Nitrogen Task and Finish Group

The SNCBs' Chief Scientists Group established a UK-wide Nitrogen 'Task and Finish' Group in June 2013. The main purpose of the group is to produce recommendations for the implementation of nitrogen deposition assessment in site-level reporting and to consider suitable actions to address nitrogen deposition on sites. This work will be completed by mid-2015.

The work is being delivered via two work streams:

- *Work Stream 1* (WS1): Attributing nitrogen impacts as a cause of unfavourable condition. A decision framework is being developed to combine the strength of theoretical/national evidence (confidence of critical load exceedance and evidence of impact) with the strength of site-based evidence to inform the attribution of nitrogen deposition as a cause of unfavourable condition or a future threat to it.
- *Work Stream 2* (WS2): Establishing solutions and mechanisms (remedies and actions) to reduce air pollution impacts on protected sites. This work stream has developed a framework for Site Nitrogen Action Plans (SNAPs). This approach is based on identifying the key nitrogen sources for each designated site as a basis to target mitigation options in the context of potential legislative, voluntary and incentive instruments. The next stage of this work will be for the country conservation bodies to implement SNAPs at sites where nitrogen deposition is identified as a key threat (based on the decision framework being developed under Work Stream 1). Currently, Natural England is developing this through their Improvement Plans for England's Natura Sites project[7]. A similar approach is being developed by Natural Resources Wales (NRW) in Wales.

3.2. APIS

The Air Pollution Information System (APIS)[8] provides an invaluable source of information in relation to air pollution impacts on habitats as well as providing site-relevant critical and deposition/concentration data. The IAPG works with the APIS partners[9] to update and improve the website. As the SNAPs concept is developed, it will drive the need to update the source attribution data in APIS.

---

[7] https://www.gov.uk/government/publications/improvement-programme-for-englands-natura-2000-sites-ipens
[8] www.apis.ac.uk
[9] A consortium consisting of all the UK SNCBs, environment agencies and CEH.

4. Evidence quality assurance

The research and evidence needs identified in the *Framework* were derived following reference to a range of recent Defra and JNCC research reports and briefings. The *Framework* was subject to peer review by members of the IAPG[10]. Comments on the draft *Framework* were also invited from other staff in the SNCBs, Defra, the Devolved Administrations, and the environment agencies; these have been recorded by JNCC.

5. Key research themes

The SNCBs are involved with, or have an active interest in, a wide range of topics relating to air pollution. This is mostly targeted around biodiversity and ecosystem services, but also includes an interest in the assessment of the co-benefits for other policy areas, such as human health. The aim of this *Framework* has been to identify the main evidence and/or research gaps in our current understanding of the impacts of air pollution on biodiversity and ecosystems. The following high-level 'themes' have been adopted within the *Framework*, in order to categorise the information:

- ecosystem responses to changes in air pollution;
- assessing and reporting air pollution impacts;
- measures and 'remedies' for air pollution.

However, there is no perfect way to categorise these different areas of interest. Whatever high-level themes are chosen, there will always be research issues/projects that could fall under different categories, cut across categories, or could be categorised separately to reflect their particular importance.

Under each theme, a summary of the main issues and the current level of understanding is provided. The *Framework* also describes the 'level of responsibility' that might be ascribed to the SNCBs in instigating research in accordance with their biodiversity duties:

- Where the SNCB involvement is fundamental, this will be described as a '**direct**' level of responsibility.
- Where participation of others is required together with the SNCBs to deliver an outcome, this will be a '**shared**' objective.
- Where the outcome, while of importance to the SNCBs, lies outwith their remit, the level of responsibility will be classified as '**indirect**'.

The level of responsibility does not prejudge future procurement arrangements for any party. It simply reflects the level of suggested engagement in future work by the SNCBs.

The following example illustrates this difference. As stated earlier, the provision of accurate deposition measurement and modelled output is vital to the SNCBs. However, the provision of the deposition data and modelled output lies outside the capability and remit of the SNCBs. The link is therefore 'indirect' (although some aspects may be 'shared' where data collected is by SNCBs and this supports national data-sets). In order to ensure up-to-date data is provided in APIS for use in impact assessments, a 'shared' approach will be required (e.g. with the UK environment agencies). The use of that data, for example in SNAPs devised by SNCBs, is a 'direct' area of responsibility.

[10] Clare Whitfield (JNCC); Gordon Wyatt, Zoe Russell (Natural England); Simon Bareham (NRW); Keith Finegan (NIEA); Alison Lee (SNH).

5.1. Theme 1: Ecosystem responses to changes in air pollution

Exposure to air pollution is subject to change, for example, as policies and local developments influence emissions, and climate change and other pollutants influence pollution dispersion patterns. Theme 1 considers research requirements to address gaps in our understanding of how ecosystems[11] will respond to future air pollution. Theme 2 then considers evidence and research needs related to the assessment and reporting of air pollution impacts; and in Theme 3 measures to reduce impacts are considered.

In this section, our current understanding of the impacts of pollutants is briefly summarised. The Government's Review of Transboundary Air Pollution (ROTAP 2012) provides further information on air pollution impacts on ecosystems. In Table 1, the key evidence areas are listed and the gaps identified.

5.1.1. Reactive nitrogen pollutants

Nitrogen deposition is comprised of both oxidised and reduced forms of nitrogen. The gases NH_3 and NOx, which contribute to nitrogen deposition, can cause eutrophication, acidification, and also directly affect vegetation. Critical levels for NOx are only likely to be exceeded close to major roads and in some urban areas (although they are not apparent from concentration maps at 5km resolution). However, there is widespread exceedance of NH_3 critical levels (data from UK NFC[12] under Defra contract AQ0826; Jane Hall, pers. comm.). In addition, nutrient nitrogen (eutrophication) critical loads were exceeded in over 65% of the area of semi-natural habitat in the UK in 2010–2012[13], and only a small decline in this exceedance is expected by 2020 (ROTAP 2012).

There is strong evidence from national surveys that nitrogen deposition has reduced plant species richness or composition in a range of habitats, and has negatively affected plant species distribution (Emmett *et al* 2011). Many of these impacts are expected to have occurred before the 1980s (Maskell *et al* 2010; Emmett *et al* 2011; ROTAP 2012). However, current nitrogen deposition is associated with further declines in sensitive plant species (Emmett *et al* 2011). In addition, some reductions in faunal diversity have been linked to nitrogen deposition, although knowledge of effects on fauna is still limited (Dise *et al* 2011). Evidence also suggests that nitrogen deposition is affecting productivity in some nitrogen-limited upland lakes (ROTAP 2012).

Nitrogen is known to accumulate in ecosystems, so impacts depend not only on current but also historic levels of nitrogen deposition. Reductions in nitrogen deposition may therefore have delayed effects, due to the persistence of nitrogen in soil and vegetation; although reductions in current deposition are likely to rapidly decrease plant exposure to nitrogen, stored nitrogen will result in a sustained release of plant-available nitrogen. Hence, cumulative deposition needs to be taken into account when considering the monitoring requirements for showing the effects of nitrogen emission reductions.

Recovery of impacts from nitrogen deposition is therefore dependent on the amount of nitrogen accumulated in the system (from previous nitrogen deposition), the amount by which nitrogen deposition declines and the level to which it declines to, and the composition of the ecological community. Recovery is possible within 1–4 years for some sensitive lichens and bryophytes, and within 5–20 years for some soil processes, plant growth and some plant species. However, because of the persistence of nitrogen in ecosystems, full

[11] The term 'ecosystem' as used throughout the document refers to the wider natural environment which includes the element of 'ecosystem services'.
[12] National Focal Centre
[13] http://jncc.defra.gov.uk/page-4245

recovery may take many decades, or may not be achievable where key species have become locally extinct.

Although nitrogen deposition is predicted to decrease at a national scale, there may be local variations (ROTAP 2012). In some cases, there may be significant increases in nitrogen deposition at a local scale, for example NH_3 hot-spots resulting from cluster developments of large agricultural, pig, poultry and dairy units. In addition, over recent years there have been significant numbers of new biomass and diesel generators located in the rural environment, which provide stand-by electricity during periods when wind power is not delivering. The units often only generate for short periods, but can produce significant local concentrations of particles and NOx. In these cases, there is a need to better understand the impacts and consequences of increasing nitrogen deposition and short-term peaks (Rowe *et al* in press(a)).

Understanding nitrogen pollutant effects, reporting on and assessing their impacts (Theme 2), and measuring the effects of actions to address nitrogen impact (Theme 3), are all dependent on exposure data of adequate quality and resolution, based on monitoring and modelling of pollutant concentrations and deposition. This is also important in respect of future pollution scenarios; for example the emission reductions of reactive nitrogen pollutants have not been translated into a similar reduction in the UK deposition budget (ROTAP 2012). This results from changes in air chemistry that mean that a proportion of the NOx generated in the UK that used to be exported is now retained and deposited in the UK as nitric acid and particulate nitrate. Better understanding of this issue, in light of nitrogen already retained in ecosystems is of profound consequence to understanding future emission–deposition scenarios. It is necessary to better understand the dynamics of these interactions to fully understand and evaluate how ecosystems may respond.

5.1.2. Ozone

Ground-level ozone is a toxic atmospheric pollutant of growing concern, with potentially harmful effects on plant communities (Morrissey *et al* 2007). It is formed in the lower atmosphere by a series of complex photochemical reactions between pollutants from a range of sources, including traffic, in the presence of sunlight. Critical levels for ozone effects on vegetation are already widely exceeded, and background levels are slowly increasing in the northern hemisphere (ROTAP 2012).

Exposure to elevated concentrations of ozone can result in visible leaf injury, reduced growth of sensitive species and reductions in crop yield, alterations of response to other environmental stresses such as drought stress, and enhanced susceptibility to pests and diseases. For example, flux-based models estimate significant reductions in crop yields as a consequence of current ozone concentrations in the UK; the loss of total national wheat yield in 2000 was approximately equivalent to 7% of production (ROTAP 2012). In addition, flux-based critical levels for forest trees are widely exceeded, as are AOT40[14] concentration-based critical levels for semi-natural vegetation.

There is evidence from experiments that ozone adversely impacts some species of semi-natural habitats. For example, experiments have shown there is a wide range in sensitivity to ozone of grassland plant and community species, suggesting that elevated ozone conditions could contribute to changes in species composition. However, it is difficult to identify ozone impacts in the field. Hence, the extent of community-level changes in semi-natural habitats in the field from ozone is unknown (ROTAP 2012).

[14] Accumulated dose of ozone Over a Threshold of 40 ppb

Unlike nitrogen and sulphur pollutants, ozone concentrations are not showing a downward trend. Although there have been reductions in peak concentrations of ozone, mean background concentrations are increasing (ROTAP 2012). There is also an increase in winter and spring episodes. Concentrations show substantial year-to-year variation because of the role of sunlight in ozone production. This means the extent of damage will vary annually, and this may have different implications for annual versus perennial species. Climate change and nitrogen deposition interactions are likely to confound the benefits of controls on ozone precursor emissions. These factors should be considered when formulating ozone monitoring options.

5.1.3. Sulphur dioxide and acidification

At peak emissions, in the 1970s, sulphur dioxide (SO_2) was responsible for widespread damage to vegetation, particularly sensitive lichen species. However, concentrations have now reduced to a level that no longer poses a risk, except in possibly a very few localised situations. Recovery is evident from recolonisation of sensitive lichens over large parts of the country formerly experiencing high SO_2 concentrations. In addition, large-scale restoration projects, in areas such as the Peak District, have demonstrated the ability of these habitats to again support sensitive bryophyte and lichen species including *Sphagnum* mosses.

Emissions of SO_2 also contribute to acidification, together with emissions of nitrogen pollutants (NOx and NH_3). The reductions in sulphur and nitrogen emissions have led to some recovery from acidification, although exceedance of critical loads is still widespread (largely due to nitrogen deposition). The legacy effects of historically high sulphur deposition are also likely to influence contemporary species richness, with current nitrogen deposition slowing recovery.

Soil acidity has declined widely in response to acid deposition reductions, and there is also widespread evidence of ongoing chemical and biological recovery of UK freshwaters. However, considerable uncertainty remains with respect to the future behaviour of nitrogen in catchments, and the extent to which further accumulation of nitrogen within soils, and the interactions with climate change, may affect the transport of nitrate to surface waters.

The dynamics of legacy stored sulphate in soils in conjunction with future nitrogen deposition in terms of future acidification prospects is also poorly understood. While the general trends show a decrease in soil acidity and exceedance of acid deposition critical loads (ROTAP 2012), the issue is far from resolved, and may continue to have significant effects in sensitive locations where the acidifying effects of sulphur persist in the soil.

Additionally, although the reduction in emissions of SO_2 from terrestrial sources (e.g. power stations and heavy industry) in the UK has been profound (94% between 1970 and 2010), emissions from international shipping in European waters have steadily increased over the same period. Emissions from shipping contribute significantly to human health impacts across Europe, as well as contributing to acid inputs to UK ecosystems. Even with the emission reductions for shipping agreed through the International Maritime Organisation (IMO), it is forecast that inputs of acidity in Europe from shipping will equal those from terrestrial sources by 2020[15]. Therefore emissions from shipping will play an increasing role as a contributor to total deposition impacts. There is a need to better understand the relevance and potential impacts from shipping to ambient air quality and their role in further acidification of UK soils and freshwaters.

[15] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/307174/impact-assessment-air-pollution-shipping.pdf

5.1.4. Heavy metals

There have been significant reductions in the emissions of heavy metals since their peak in the 1970s. The greatest reductions have been in recent years following the introduction of the CLRTAP 1998 Protocol on Heavy Metals with, for example emissions of lead and mercury declining by approximately 32% and 24% respectively. Atmospheric concentrations of metals in rural and industrial/urban areas have also declined. In addition, deposition has reduced by approximately 36% (lead) and 33% (mercury) (ROTAP 2012).

However, it has been noted that for many metals, there are large discrepancies between emission estimates and measured deposition, with deposition being up to a factor of 10 greater than emission estimates. Re-suspension of deposited metals may play a significant role in particular catchments, and further work is needed to reconcile the emission–deposition anomaly. At present there is too little quantitative information to identify the sources of the metals currently recorded in UK air.

Critical loads have been derived for a range of metals (cadmium, lead, copper, nickel and zinc) for six UK habitats. The results show (for example) that over 50% of the area of managed broad-leaved woodland and unmanaged woodland exceed their critical load for copper, lead and zinc (ROTAP 2012), based on modelled deposition.

Levels of copper and lead already in UK soils are unlikely to decrease significantly for many centuries.

Table 1. Theme 1: Ecosystem responses to changes in air pollution. Areas for future research/evidence needs.

Key research and evidence needs	Responsibility	Examples of research or evidence needs	Policy Relevance	Operational Relevance
Sub-theme: All Pollutants				
Air pollution impacts on ecosystems' resilience to other pressures (note link to JNCC and partners' work on resilience: interaction of other pressures with invasive species/pests and pathogens).	Shared	a) How does air pollution modify or influence other pressures (e.g. on non-plant species, invasive species, pests and diseases)? (i.e. assess direct and indirect impacts). b) What is the relative importance of pollution in driving habitat change alongside other drivers, and how beneficial are emission reductions compared to action on other pressures? c) Are air pollution effects influencing the potential resilience of ecosystems to future climate change?	• EU and country biodiversity strategies • Habitats Directive and national designated sites legislation	• Assessing / maintaining / restoring site or species condition
Understanding interactions between climate change and air pollution. There is a need to integrate climate and air pollution (particularly nitrogen and ozone) scenarios to better understand climate change/ air pollution impacts at sites.	Shared	d) Assess the impacts of climate/pollution interactions on ecosystems via experimental and modelled studies (building on existing studies). e) Improve understanding of the effects of extreme climate events on nitrogen dynamics and the impacts on ecosystems. f) How will predicted changes in Jet stream/wind direction and precipitation driven by climate change impact on future pollution dispersion, in both a long-range and local modelling context?	• NECD/Gothenburg Protocol • Habitats Directive and national designated sites legislation • EU and country biodiversity strategies • UK climate change programme/policy • Industrial Emissions Directive (IED)	• Casework advice • Assessing / maintaining / restoring site or species condition
Impact of air pollutants on non-plant species and on less well researched habitats.	Shared	g) What are the impacts of air pollutants on species other than vegetation (e.g. fauna, fungi), and what are the consequences of this for ecosystem function, services and biodiversity commitments? h) What is the sensitivity of Annex I habitats (particularly to nitrogen) for which a relevant critical load is not available?	• Habitats Directive • EU and country biodiversity strategies • Industrial Emissions Directive (IED)	• Casework advice • Article 17 reporting • Assessing / maintaining / restoring site or species condition

Key research and evidence needs	Responsibility	Examples of research or evidence needs	Policy Relevance	Operational Relevance
Relationships between pollutant (particularly NOx and NH_3) emissions and deposition.	Indirect	i) Continued collection of concentration-flux relationship data to support understanding between emissions and deposition and non-linearity. j) Assessment of spatial variation in uncertainty of emissions and deposition. k) Evaluation of future shipping emissions and consequences for deposition (particularly nitrogen deposition) after 2020.	• NECD/Gothenburg Protocol • Industrial Emissions Directive (IED) • UK policy analysis	• SNAPs • Casework advice • Site condition assessment
Assessing impacts of short-term exposure risks.	Shared	l) What are the risks of short-term peaks of atmospheric pollutants on ecosystems? Consequently, are there short-term CL or Environmental Assessment Levels (EALs) which should be used in casework?	• Habitats Directive	• Casework advice
Sub-theme: Reactive nitrogen pollutants				
Understanding of ecosystem responses to future emission/deposition scenarios.	Shared	m) Better understanding and evaluation of the role of existing deposited nitrogen in ecosystems in the context of climate change. What are the implications of cumulative nitrogen in respect of future nitrogen deposition impacts and recovery? n) Only a small proportion of deposited nitrogen currently leaks into surface waters. Will the major increases in nitrate leaching predicted by mass-balance models occur over policy-relevant timescales (years to decades) and what are the implications? See also Theme 2.	• NECD/Gothenburg Protocol • Habitats Directive and national designated sites legislation • EU and country biodiversity strategies	• Casework advice • Assessing / maintaining / restoring site or species condition • Setting conservation objectives for sites/species

Key research and evidence needs	Responsibility	Examples of research or evidence needs	Policy Relevance	Operational Relevance
Improved quantification of NH_3 emissions, particularly from cattle, and improved spatial mapping of emissions.	Indirect	o) More accurate calculation of sectorial emission factors (particularly from the agricultural sector), qualification of uncertainties, including local factors – and extent of certainty required for different uses to which the data will be put.	• Habitats Directive and national designated sites legislation • NECD/Gothenburg Protocol • Industrial Emissions Directive (IED)	• Casework advice • SNAPs • Emission inventories
Sub-theme: Ozone				
Understanding the reasons for steady rises in ozone concentrations and the potential impacts on habitats.	Indirect	p) Work at a northern hemisphere scale to assess the relevance and role of ozone precursor sources, such as biomass burning and shipping. q) Production of more accurate long-term ozone/ climate change scenarios (~20–30 years), and assessment of impacts on ecosystems taking into account nitrogen and climate change impacts.	• NECD/Gothenburg Protocol • Habitats Directive and national designated sites legislation • EU and country biodiversity strategies	• Quantifying threat to designated sites/species
Sub-theme: Atmospheric deposition of heavy metals				
The extent to which heavy metals pose a threat to biodiversity in the UK.	Indirect (Shared)	r) Develop accurate source attribution of heavy metals in the UK. s) Development work on critical loads, to understand the dynamics of change in heavy metal exposure and the threat to UK soils and aquatic ecosystems and impacts on species. t) What is the effect of heavy metals on ecosystem function?	• EU and country biodiversity strategies • Industrial Emissions Directive (IED)	• Casework advice

5.2. Theme 2: Assessing and reporting air pollution impacts

Theme 2 covers the assessment of air pollution impacts and the use of this evidence in reporting and other analysis. The SNCBs have a number of existing projects or initiatives in place aimed at addressing issues and gaps previously identified through research studies and reporting exercises. The evidence gaps also need to be considered in light of the Defra ONE monitoring review, and as with each theme, the Defra Network Evidence Action Plans (NEAPs), and similar initiatives in the Devolved Administrations.

This section focuses mainly on nitrogen pollutants, considering evidence from monitoring and the metrics used to assess impacts. This is followed by a brief consideration of acidification and ozone.

5.2.1. Reactive nitrogen pollutants

Evidence from monitoring
A substantial analysis of broad-scale vegetation data-sets was undertaken for the SNCBs and Defra by Stevens *et al* (2011), to elucidate the role of nitrogen deposition in driving plant species distribution and habitat-level changes. This has contributed to the strong evidence base of nitrogen impacts described in Section 5.1. The new JNCC-led National Plant Monitoring Scheme (NPMS[16]) will provide a resource to refresh this evidence to show ongoing damage and/or recovery in terrestrial habitats. The approach also relies on the continued and sufficient monitoring of pollution air concentrations and deposition (e.g. through the UKEAP[17] network), in order to maintain a national deposition model with sufficient resolution and accuracy. Other site data such as from Natural England's Long Term Monitoring Network may also provide valuable data over time.

It is important to maintain this evidence base in order to show the effects of nitrogen deposition on vegetation (i.e. to detect where impacts are ongoing and whether recovery is commencing in some areas and how this is manifest). Nitrogen deposition has driven changes in plant communities and species distribution via both eutrophication effects and acidification effects, and monitoring may also help attribute the mechanism of impact. Recovery in response to a future decrease in nitrogen deposition will vary spatially, depending partly on historic nitrogen inputs, habitat type, and also where reduction measures are targeted. Rates of biogeochemical recovery in terrestrial ecosystems are likely to be faster than recovery of vascular plant communities, which may be slow. Therefore, any monitoring would usefully include intermediary measures, such as nitrogen availability in soils, as well as vegetation response.

Despite the strong evidence base of nitrogen deposition impacts, it remains a challenge to attribute nitrogen impacts on an individual site within our current framework for site assessment, Common Standards Monitoring (CSM). Consequently, the role of nitrogen deposition is currently under-reported.

Identifying priorities for action, and the targeting of measures (Theme 3) to address pressures on habitat condition, is likely to focus on sites in unfavourable condition and on identified causes of unfavourable condition. This is a problem in respect of tackling nitrogen deposition impacts if they are not reported as a concern at the level of individual sites. To address this, the Nitrogen Task and Finish Group are developing a decision framework to use national and site data to attribute nitrogen deposition as a cause of unfavourable habitat condition or as a future threat. The outcomes of this work will inform future research and development needs.

[16] http://www.brc.ac.uk/npms/content/welcome
[17] http://uk-air.defra.gov.uk/networks/network-info?view=ukeap

The extent to which nitrogen deposition is a concern in wetland systems is being investigated in an ongoing project funded by the Environment Agency and the British Geological Society. This will examine the nitrogen budgets and source apportionment (including both atmospheric and terrestrial sources) at a site level. It will determine whether it is possible to identify the main pressure contributing towards unfavourable condition between atmospheric deposition, terrestrial nitrate and poor site management.

Critical loads and metrics

Critical loads are currently the main tool used in risk assessment of nitrogen deposition impacts, both for national-scale evaluation of policies and for site-specific impact assessment. There is strong evidence that exceedance of critical loads is associated with negative impacts on terrestrial biodiversity at the UK scale (ROTAP 2012).

The effectiveness of emission reduction policies can be assessed by comparing the extent of critical load exceedance either on a per cent of habitat area basis, or using Average Accumulated Exceedance. For example, the assessment of nitrogen deposition, and acid deposition, as a pressure and threat to conservation status under Article 17 reporting in 2007 and 2013 used critical loads exceedance data[18] in addition to CSM data. Average Acumulated Exceedance (AAE) provides a measure of change even where there may be little change in the area exceeded, but currently it is not commonly reported (e.g. UK Biodiversity Indicators[19]).

However, analyses based on critical load exceedance do not consider the cumulative doses of nitrogen. They do not tell us how, and over what timescales, ecosystems will respond to reductions in deposition, which nevertheless may continue to be above the critical load, although it is necessary to understand this to inform future policies on emissions and also the implications of the ongoing threat to the status of habitats.

Consequently, in 2013 Defra commissioned a study to provide an overview of the current knowledge base in respect of cumulative impacts and recovery, and to evaluate and recommend metrics to show the benefits of reductions in nitrogen deposition (Rowe *et al* in press(a)). The project also identified evidence gaps and made recommendations for future research. The study recommended metrics of *pressure*; *midpoint* metrics that indicate progress towards biodiversity targets and other goals in terms of ecosystem functions and services; and *endpoint* metrics that represent the degree to which these goals have been achieved. Most promising, in the short term, was a metric based on integrating deposition over 30 years (for soil-based habitats) in order to represent persistent effects. However, there are still areas of large uncertainty, including ecosystem responses to marginal decreases in nitrogen deposition and capacity to simulate and predict changes.

Two further studies commissioned by Defra were aimed at developing a ‘biodiversity indicator’ in response to the 2012-14 ‘Call for Data’ from the Co-ordination Centre for Effects under the CLRTAP (Rowe *et al* in press(b,c)). In the first of these studies, habitat experts from the SNCBs were consulted, and agreement was reached that the basis for this biodiversity indicator should be the habitat suitability for CSM positive indicator-species. In the second study (Rowe *et al* in press(c)), values for an indicator of this type were calculated for 18 example sites under two scenarios. There is potential for this habitat quality index to be developed further to derive critical loads, and a study has recently been commissioned by Defra for this purpose (in response to a ‘Call for Data’ from the Co-ordination Centre for Effects).

[18] http://jncc.defra.gov.uk/article17
[19] http://jncc.defra.gov.uk/page-4229

Despite the studies already being undertaken, it remains important to understand, and have suitable metrics or tools to:

- analyse the ‘future prospects’ of habitats in light of reducing nitrogen deposition but often increasing cumulative load;
- analyse the extent to which reductions are necessary to ensure future viability of the habitat;
- assess the implications of small additional increments of nitrogen through new plans and projects (often against a small reduction in background deposition).

5.2.2. Acidification

There has been some chemical and biological recovery from acidification in sensitive freshwaters. However, recovery has not been full, and there is a need to continue to assess recovery and understand the factors limiting it, in order to inform future policy. This need is currently met via the Uplands Waters Monitoring Network (UWMN). Impacts of acidification are considered within CSM for freshwaters via inclusion of attributes for Acid Neutralising Capacity (ANC) and pH. Therefore, the extent to which this is a problem for site/habitat will be reflected in reporting on site condition/conservation status.

Terrestrial habitats are also impacted by acidification. For example, Stevens *et al* (2010) showed that changes in species richness in acid grassland were driven by acidification effects from nitrogen deposition. Since nitrogen deposition is the main driver of this impact, it is considered as part of the nitrogen deposition section (above).

5.2.3. Ozone

In respect of natural and semi-natural habitats, experimental evidence suggests there is an impact on plant communities from ozone. This has not been translated into an understanding of the broad-scale or site-specific effects on habitat structure and function, and hence has not been included in reporting (for example Article 17). Measures or indicators do not currently exist to demonstrate the extent of impacts on natural and semi-natural habitats and how this is changing over time.

Table 2. Theme 2: Assessing and reporting air pollution impacts. Areas for future research/evidence needs.

Key research and evidence areas	Responsibility	Examples of research or evidence needs	Policy relevance	Operational relevance
Surveillance and monitoring to show ongoing damage and/or recovery in terrestrial and freshwater habitats at broad-scale and local level.	Shared	a) Much of the evidence needs in this area are, or will be, delivered through current initiatives. For example: (1) maintain ability to undertake broad-scale analysis of N impacts (e.g. using the NPMS); (2) the requirement to identify N as a cause of unfavourable condition or future threat on protected sites will be addressed by the development, and future implementation of, the decision framework being produced by the Task and Finish Group work; (3) there is a need to continue to assess recovery from acidification in freshwaters and understand the factors limiting it (see also Theme 1). b) No other specific recommendations for new research are made at this point. There is a need to review research needs following completion of the Task and Finish Group's decision framework, and in light of its recommendations. Also there is a requirement to continue to ensure this evidence area is fully considered, where relevant, in reviews of current surveillance and monitoring schemes (including atmospheric pollution monitoring).	• NECD/Gothenburg Protocol • EU and country biodiversity strategies • Habitats Directive and national designated sites legislation	• Informing SNAPs (see Theme 3) • Article 17 reporting • Site condition assessment • Casework advice
Develop and apply metrics to help evaluate future prospects of habitats and inform objective setting for habitats/sites. Improve understanding of response of habitats in light of reducing nitrogen deposition, but with cumulative loads (links to Theme 1).	Shared	c) Develop a metric based on cumulative N deposition calculated over a representative threshold and period (e.g. above CL_{nutN} for preceding 30 years). Analyses could be directed at establishing response functions to a pre-defined metric of cumulative N, or towards establishing which metric of cumulative N best explains response data. This could be based on statistical exploration of data-sets that have already been analysed in relation to current and total cumulative deposition.	• NECD/Gothenburg Protocol • Habitats Directive	• Deposition scenario analysis • Casework advice • Article 17 reporting • Setting conservation objectives for sites/species

Key research and evidence areas	Responsibility	Examples of research or evidence needs	Policy relevance	Operational relevance
		d) Develop metrics/measures based on habitat quality against which to set CL, ultimately for use in assessing deposition future scenarios, informing casework decisions and assessment of conservation status.		
Habitat mapping – site relevant critical loads (critical loads have been assigned to interest features in protected sites).	Direct	e) Digital, spatial data on the location of the habitat features in the sites, to provide more spatially accurate critical loads for protected sites.	• Habitats Directive • CLRTAP/EU policy analysis (Natura 2000 CL exceedance) • EU and country biodiversity strategies	• Article 17 reporting • Site condition assessment • Casework advice • SNAPs
Habitat mapping – national critical loads (national critical loads maps are based on habitat mapping from LCM2000 and ancillary data).	Direct	f) No other specific recommendations for new research are made at this point. However, country agency (and other) habitat mapping initiatives should consider CL mapping as potential data users.	• CLRTAP/EU policy analysis (Natura 2000 CL	• National policy appraisals • BIYP
Deposition and concentration mapping.	Indirect	g) Improve accuracy and spatial resolution of concentration and deposition maps, and support this with improved emission inventories (this also relates to Theme 3 and the need to establish a baseline from which actions can be delivered).	• Habitats Directive • Policy analysis • EU and country biodiversity strategies	• Article 17 reporting • Site condition assessment • Casework advice • SNAPs
Investigate the impacts of ozone on habitat structure and function and species distribution.	Shared Indirect	h) Analysis of broad-scale vegetation data-sets to show whether ozone is driving species-level responses. i) Develop flux-based metrics for semi-natural habitats based on improved understanding of habitat structure and function impacts.	• EU and country biodiversity strategies	

Key research and evidence areas	Responsibility	Examples of research or evidence needs	Policy relevance	Operational relevance
Ecosystem services and valuation.	Indirect	j) Assess marginal (incremental) impacts on ecosystem services to provide valuation, building on recent work (Defra), and prioritising services based on gap analysis undertaken by Jones *et al* (in press). This will include development of dose response functions, which require an improved understanding of the implications of marginal reductions in pollutants, which can be difficult where the recovery pathway is different from that of the damage pathway (or where this is unknown). Note that the EU MAES project (http://biodiversity.europa.eu/maes) is likely to include an air pollution pilot project (relates also to Theme 1).	• UK/EU policy analysis	
Acidity and N impacts on freshwaters.	Shared	k) Determine whether nutrient N critical loads and acidity critical loads can and should be applied to freshwater sites for purposes of casework and judging future prospects (see also Theme 1) l) Review how dynamic models could be used to inform our assessment approach for acidification impacts on terrestrial habitats and freshwaters. Run a range of scenarios to assess implications of acid inputs using on steady-state critical loads and those based on dynamic modelling. m) Determine the role of atmospheric sources of N in Water Framework Directive (WFD) compliance (see Environment Agency BGS project described in Section 5.2.1)	• Habitats Directive and national designated sites legislation • Water Framework Directive (WFD)	• Casework advice • WFD plans • Site condition and threat assessment

5.3. Theme 3: Measures and remedies

Theme 1 focussed on understanding the processes and mechanisms of current and future impacts of air pollution on biodiversity, whilst Theme 2 considered the assessment and reporting of those impacts. Theme 3 concentrates on measures to address air pollution impacts and the tools required to support this. While the SNCBs' focus is mainly on the protected site network, for which they have responsibility, the approach is equally applicable to the wider countryside.

5.3.1. Background

As discussed previously the *Framework* has focussed on a range of air pollutants. However, when considering measures and remedies the priority area of focus is mostly on nitrogen pollution.

Nitrogen deposition is a pressure on the conservation status of habitats and a threat to their future prospects. Nitrogen pollutants also contribute to impacts on human health, soil and water quality. A range of drivers exist to deliver environmental protection to these receptors, but effort has traditionally been focussed on protection of a single receptor, be it water quality or human health. It is necessary to identify the co-benefits and trade-offs between these different policy drivers, to inform integrated policies and measures aimed at delivering multiple benefits.

While measures to tackle nitrogen impacts are required at an international- and national-scale, there is increasing interest in local-scale measures to reduce inputs at the site level. These range from consideration of abatement of local emission sources through to the use of practical measures that can be targeted at sites. However, in order to drive local measures it is necessary to have a high level of confidence regarding the deposition estimates at a site and on the source attribution of that deposition.

The use of local measures adopted throughout Europe was discussed in detail at the recent Nitrogen Deposition and the Nature Directives Workshop, held in Peterborough in 2013 (Whitfield and McIntosh 2014). Measures, their cost effectiveness, and delivery mechanisms have recently been subject to review by Dragosits *et al* (in prep(a)) as part of a study to provide a framework for Site Nitrogen Action Plans (SNAPs).

5.3.2. Local versus national measures

Total UK deposition of nitrogen compounds is more-or-less equally divided between oxidised (NO_x) and reduced (NH_x) forms. Oxides of nitrogen originate primarily from combustion sources, including power generation, vehicles, industrial processes and domestic heating. These emissions have been significantly reduced over recent years and further reductions are committed to under current legislation. In terms of NH_3 emissions, approximately 90% originates from agricultural activity. Emissions of NH_3 have reduced considerably less than for NOx, and indeed in areas such as Northern Ireland and Wales levels have increased since 2008 (NAEI 2014).

Source attribution studies carried out by Dragosits *et al* (in prep(a)) and further developed under the IPENS project have shown that the relative contributions of NO_x and NH_x from the various sectors (e.g. agriculture, industry, transport, power generation, shipping) vary considerably between different locations. Ammonia in particular displays a wide spatial variation in concentration and NH_x deposition, with hotspots close to areas of large agricultural activity. Long-range emissions contribute the major input to remote upland sites experiencing high rainfall. Site Nitrogen Action Plans (SNAPs) will therefore need to take account of these variations in order to ensure that the most appropriate and cost-effective set of emission reduction measures are selected for any particular site.

At the present time, the most cost-efficient approach to the reduction of nitrogen deposition is to target NH_3 reduction measures around sensitive designated sites, as this will achieve a reduction in local impacts as well as contributing to overall national emission reductions (Dragosits *et al* in prep(b)). The larger poultry and pig units are regulated by the UK environment agencies under the Industrial Emissions Directive (IED), and enforceable NH_3 emission limits can be set. However, these units are only responsible for approximately 5% of UK NH_3 emissions; the remaining agricultural NH_3 emissions arising from smaller pig and poultry units, cattle and other livestock, and volatilisation following the application of fertilisers, organic wastes and leachates to land. In order to start to address the issue of NH_3 from farms which fall outside the IED regulations, a suite of NH_3 reduction measures are being introduced in England as part of the new Countryside Stewardship Scheme and Countryside Productivity Scheme. Similar proposals are being considered in Wales under proposals for the Rural Development Programme to support agri-environment-climate measures, organic farming and capital investments for sustainable agricultural production practices.

Table 3. Theme 3: Measures and remedies. Areas for future research/evidence needs

Key research and evidence needs	Responsibility	Examples of research or evidence needs	Policy Relevance	Operational Relevance
Measures to reduce impacts.	Shared	a) Identify 'best practice' methods to integrate measures for agricultural diffuse pollution to both air and water and identify win-wins. b) Examine co-benefits of tackling local rural NH_3 sources for biodiversity protection and human health (e.g. formation of urban $PM_{2.5}$ by ammonium nitrate). c) Address outstanding gaps to demonstrate what restoration measures can help maintain (or improve) habitat quality in situations where nitrogen deposition remains too high. d) Develop a better understanding of the potential co-benefits around the spatial targeting of agricultural pollution to achieve multiple outcomes.	• NECD/Gothenburg Protocol • Air Quality Directive • Habitats Directive	• Local Air Quality Management • Agri-environment • SNAPs
Emissions and deposition.	Shared	e) Establish historic and future deposition trends at sites as a result of (inter)national measures. f) Update and maintain national source attribution data. A more detailed source attribution data-set is required allowing the proportion of long-/medium-/short-range N inputs at each site for each source type. g) Ensure data is gathered on the extent of uptake of mitigation measures and spatial distribution, and that these changes can be reflected in national emissions database and to demonstrate effectiveness of emissions reductions.	• Policy analysis • NECD/Gothenburg Protocol	• SNAPs • Casework advice
Tools to support SNAPS and other mitigation.	Shared	h) Develop a web tool to enable the assessment of the contribution of multiple spatially separate sources and the effect of potential measures.		• SNAPs • Casework advice

6. References

DISE, N.B., ASHMORE, M., BELYAZID, S., BLEEKER, A., BOBBINK, R., DE VRIES, W., ERISMAN, J.W., SPRANGER, T., STEVENS, C.J. & VAN DEN BERG, L. 2011. Nitrogen as a threat to European terrestrial biodiversity. In: M.A. SUTTON, C. HOWARD, J.W. ERISMAN, G. BILLEN, A. BLEEKER, P. GRENNFELT, H. VAN GRINSVEN & B. GRIZZETTI, eds. *The European Nitrogen Assessment*. Cambridge: Cambridge University Press, 463–494.

DRAGOSITS, e*t al*. in prep(a). Identification of potential remedies for air pollution impacts on designated sites (RAPIDS). Defra.

DRAGOSITS, *et al*. in prep(b). Future patterns of ammonia emissions across the UK and the potential impact of local emission reduction measures. Defra.

EAC. 2013. House of Commons Environment Audit Committee Report. Air Quality: A Follow up report, ninth report of session 2010-2012, HC1024.

EEA. 2014. Air Quality in Europe – 2014 Report. EEA Report No. 05/14.

EMMETT, B.A., ROWE, E.C., STEVENS, C.J., GOWING, D.J., HENRYS, P.A., MASKELL, L.C. & SMART, S.M. 2011. Interpretation of evidence of nitrogen impacts on vegetation in relation to UK. JNCC Report No. 449. Available from: http://jncc.defra.gov.uk/page-5895 [Accessed January 2015].

JONES, L., MILLS, G., MILNE, A., HAYES, F., MONTEITH, D., DWYER, J., OZDEMIROGLU, E., HALL, J., EVANS, C., EMMETT, B., SUTTON, M., REIS, S., ASHMORE, M., EVERARD, M. & HOLLAND, M. in press. Assessment of the impacts of air pollution on ecosystem services – gap filling and research recommendations. Defra Project AQ0827, Final Report.

MASKELL, L.C., SMART, S.M., BULLOCK, J.M., THOMPSON, K. & STEVENS, C.J. 2010. Nitrogen deposition causes widespread loss of species richness in British habitats. *Global Change Biology*, **16**, 671–679.

MORRISSEY, T., ASHMORE, M.R., EMBERSON, L.D., CINDERBY, S. & BUKER, P. 2007. The impacts of ozone on nature conservation. JNCC Report No. 403.

NAEI. 2014. National Atmospheric Emissions Inventory: Air pollutant Inventories for England, Scotland, Wales and Northern Ireland: 1990–2012, October 2012.

OECD. 2012. *OECD Environmental Outlook to 2050: the consequences of Inaction*, 350 pp.

ROTAP. 2012. Review of Transboundary Air Pollution, Acidification, Eutrophication, Ground Level Ozone and Heavy Metals in the UK. Defra. Available from: http://www.rotap.ceh.ac.uk [Accessed January 2015].

ROWE, E.C., JONES, L., STEVENS, C.J., VIENO, M., DORE, A.J., HALL, J., SUTTON, M., MILLS, G., EVANS, C.D., HELLIWELL, R.C., BRITTON, A.J., MITCHELL, R.J., CAPORN, S.J., DISE, N.B., FIELD, C. & EMMETT, B.A. in press(a). Measures to evaluate benefits to UK semi-natural habitats of reductions in nitrogen deposition. Final report on REBEND project (Defra AQ0823; CEH NEC04307). Centre for Ecology and Hydrology, Bangor, LL57 2UW, UK. 73 pp.

ROWE, E.C., FORD-THOMPSON, A., MONTEITH, D., VAN HINSBERG, A., SMART, S., HENRYS, P. & ASHMORE, M. in press(b). A biodiversity metric for interpreting outputs of models of atmospheric nitrogen pollution impacts on habitats. Final report on DivMet1 project (Defra AQ0828; CEH NEC04988). Centre for Ecology and Hydrology, Bangor, LL57 2UW, UK. 94 pp.

ROWE, E.C., JARVIS, S., HALL, J., MONTEITH, D., HENRYS, P., EVANS, C.D. & SMART, S. in press(c). Operationalising a metric of nitrogen impacts on biodiversity for the UK response to a data request from the Coordination Centre for Effects. Final report on DivMet2 project (Defra AQ0832; CEH NEC05090). Centre for Ecology and Hydrology, Bangor, LL57 2UW, UK. 24 pp.

STEVENS, C. 2010. Nitrogen deposition threatens species richness of grasslands across Europe. *Environmental Pollution*, **158**(9), 2940–2945.

STEVENS, C.J., SMART, S.M., HENRYS, P.A., MASKELL, L.C., WALKER, K.J., PRESTON, C.D., CROWE, A., ROWE, E.C., GOWING, D.J. & EMMETT, B.A. 2011. Collation of evidence of nitrogen impacts on vegetation in relation to UK biodiversity objectives. *JNCC Report* No. 447.

WHITFIELD, C. & MCINTOSH, N. 2014. Nitrogen Deposition and the Nature Directives Impacts and Responses: Our Shared Experiences. Report of the Workshop held 2-4 December 2013. *JNCC Report* No. 521.