JNCC Report 757

Scoping Future Research for Air Pollution Recovery Indicators (APRI)

(Workshop Report)

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Evidence Quality Assurance:
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Summary

Atmospheric nitrogen (N) pollution is a major and ongoing cause of biodiversity loss across the UK, but in some locations N pollution pressures have been declining. In response to these dynamics, JNCC requested a workshop to help to scope Phase 2 of the Air Pollution Recovery Indicators (APRI) project. The damaging effects of excess N load and of gaseous ammonia on many ecosystems are clear. However, the processes and timescales of ecosystem recovery following a decrease in pollution pressure are less well understood. The APRI project aims to take practical steps to fill this knowledge gap by delivering new scientific research focused on indicators of ecosystem and species recovery from N pollution. In Phase 1, predominantly below-ground responses are being studied at a dry heathland site where experimental additions of N were made between 1998 and 2011, revealing lingering effects on soil chemistry, the soil fungi community and vegetation structure (Kowal *et al.* 2024). The effect on mycorrhizal fungi, and using these fungi as recovery indicators, is being examined in more detail with recently established assessment methods (Arrigoni *et al.* 2023). Phase 2 of APRI will consider recovery from N impacts more broadly, e.g. by studying other habitats or species. Further empirical research may be commissioned to better understand recovery pathways from air pollution.

A workshop was held on 7–8 November 2023 to help develop an action plan for the remainder of the APRI project. This report summarises the workshop discussion and ensuing work. We note that the focus of the APRI project is on assessing recovery. It is therefore essential to contrast responses of ecosystems subject to decreased pollution pressure with indicators from ecosystems experiencing ongoing pollution. Properties that have been used previously to assess impacts can be used to understand recovery, and novel indicators of ecosystem change are also likely to be useful for assessing recovery. Whatever indicators are chosen to assess change, benchmarking data will be needed to assess the range of potential values and relationships with N deposition.

Results from the workshop and subsequent discussions include:

- Eleven criteria to help choose appropriate indicators in relation to declining N deposition: Speed of response, Sensitivity of response, Specificity of response, Generality to multiple habitats, Relatedness to recovery endpoints, Previous use, Breadth of pollution gradient, Added value to other policy areas, Resilience in face of anticipated change, Feasibility of collection, Measurement uncertainty.
- The need to consider a basket of indicators to indicate recovery from N pollution. Such a basket could include examples from different categories e.g. indicators of pressure, biogeochemical response indicators, and biotic response indicators, with individual indicators likely responding over different timescales. The exact choice may depend on the habitat concerned and the availability of prior data, as well as the question being posed and/or policy goal.
- Explicit recommendations on sites to target in APRI Phase 2 to gain information on recovery indicator trajectories, namely (i) well-designed field experiments where N addition has ceased, and (ii) point sources of emissions that have ceased to operate, preferably with a super-imposition of an experimental treatment or treatments. Given uncertainties associated with modelled historical, contemporary, and future N deposition and the potential for confounding variables, analysing survey data from across the UK will be unlikely to provide robust information within the timeframes of the APRI Phase 2.

We recommend further assessments may help develop detailed plans for empirical work in Phase 2 of APRI. Potential next steps are to:

- Finalise a list of potential and priority indicators of recovery from air pollution (which may differ by habitat type), specifically from high levels of N deposition and/or high atmospheric reactive N concentrations. This finalisation could be done through active participation of the air pollution community and the completion of 'live' spreadsheets that address potential indicator criteria.
- Summarise relevant data on recovery indicators, across key semi-natural habitats. This summary should include data available from other countries with similar environmental contexts, to help disentangle drivers of change in the UK context. This evidence will help understand recovery pathways from air pollution. As above, this could be done through the active participation of the air pollution community and the completion of 'live' spreadsheets. Such an approach could also enable gap analyses, for example identifying where we are missing information by habitat and/or environmental conditions.
- Identify areas where co-located monitoring of N with existing habitat/species monitoring could enhance the likelihood for establishing recovery indicators. This should enhance other similar activity such as through the Natural Capital and Ecosystem Assessment programme and the UK Air Pollution Impacts on Ecosystems Networks (APIENs).
- Develop a list of priority habitats and sites where empirical research is needed to better understand recovery pathways, including a gap analysis of habitats, methods and/or indicators.
- Encourage activities that enhance understanding of ammonia emission sources at local scale (e.g. 1 km or less), to help better identify areas where N pollution has decreased, and recovery might be detected. This could include intensive monitoring or collating and sharing information about permitted N sources.
- Develop case studies, including potentially from APRI Phase 1, to demonstrate how existing evidence on localised recovery in semi-natural habitats of conservation importance can be used by policy- and decision-makers to help drive policy toward continued reductions in emissions of reactive N.

Contents

1. Introduction

1.1. Nitrogen Impacts vs Nitrogen Recovery: What we know vs what we don’t know

Atmospheric nitrogen (N) pollution is a major and ongoing cause of biodiversity loss across UK habitats (e.g. Phoenix *et al.* 2012; Field *et al.* 2014; Southon *et al.* 2013), and globally (e.g. Harpole *et al.* 2016; Gilliam 2006; Staude *et al.* 2020). The damaging effects of excess N load and of gaseous ammonia on many ecosystems are clear (Figure 1) and undesirable in the context of conservation goals that support ecosystem function and ‘normal’ N cycling. **Impacts** include community composition change (Perring *et al.* 2024), loss of rare species (e.g. Staude *et al.* 2020), homogenization of biota, acidification, increased resource supply rates, and more open nutrient cycles which can lead to eutrophication in terrestrial and aquatic systems (Galloway *et al.* 2008). Some ecosystem changes can occur over short timescales, whilst others take decades since they require species assemblages to reorder (cf. the Hierarchical Response Framework; Smith, Knapp & Collins 2009). In some instances, for example if invasive species and/or exotic pests and pathogens are favoured by resource alteration, changes in structure and function can occur over relatively short time periods (Smith, Knapp & Collins 2009). On the other hand, buffering effects may prevent change in components of some habitats, for instance limited understorey community change in forests due to overstorey buffering (Landuyt *et al.* 2024).

The processes and timescale of **recovery** following a decrease in pollution pressure are less well understood, although there is some evidence related to delays in recovery in a UK context (e.g. Pakeman *et al.* 2019; Edmondson *et al.* 2013; Kowal *et al.* 2024) as well as evidence of at least partial recovery elsewhere (e.g. van Strien *et al.* 2018). However, as air pollution policies and technological advances continue to deliver declines in atmospheric concentrations of some N-containing pollutants (e.g. Garland *et al.* 2023), there is a pressing need to understand how ecosystems and species recover from the impacts of previous N deposition (e.g. Schmitz *et al.* 2024; Gilliam *et al.* 2024; Stevens 2016), how any recovery may be affected by the changing ratio of reduced and oxidised N forms in contemporary deposition profiles, and whether policy aims are being achieved. Indeed, UK trends in atmospheric composition and deposition need to be considered when considering recovery from N pollution. For instance, the larger decreases witnessed over the last decades for sulphur dioxide (SO_2) and nitrogen oxides (NO_X) atmospheric concentrations may result in greater environmental impacts of reduced N (e.g. NH_3) at lower concentrations than previously understood (Sutton *et al.* 2020). Such alterations may confound simple expectations of recovery.

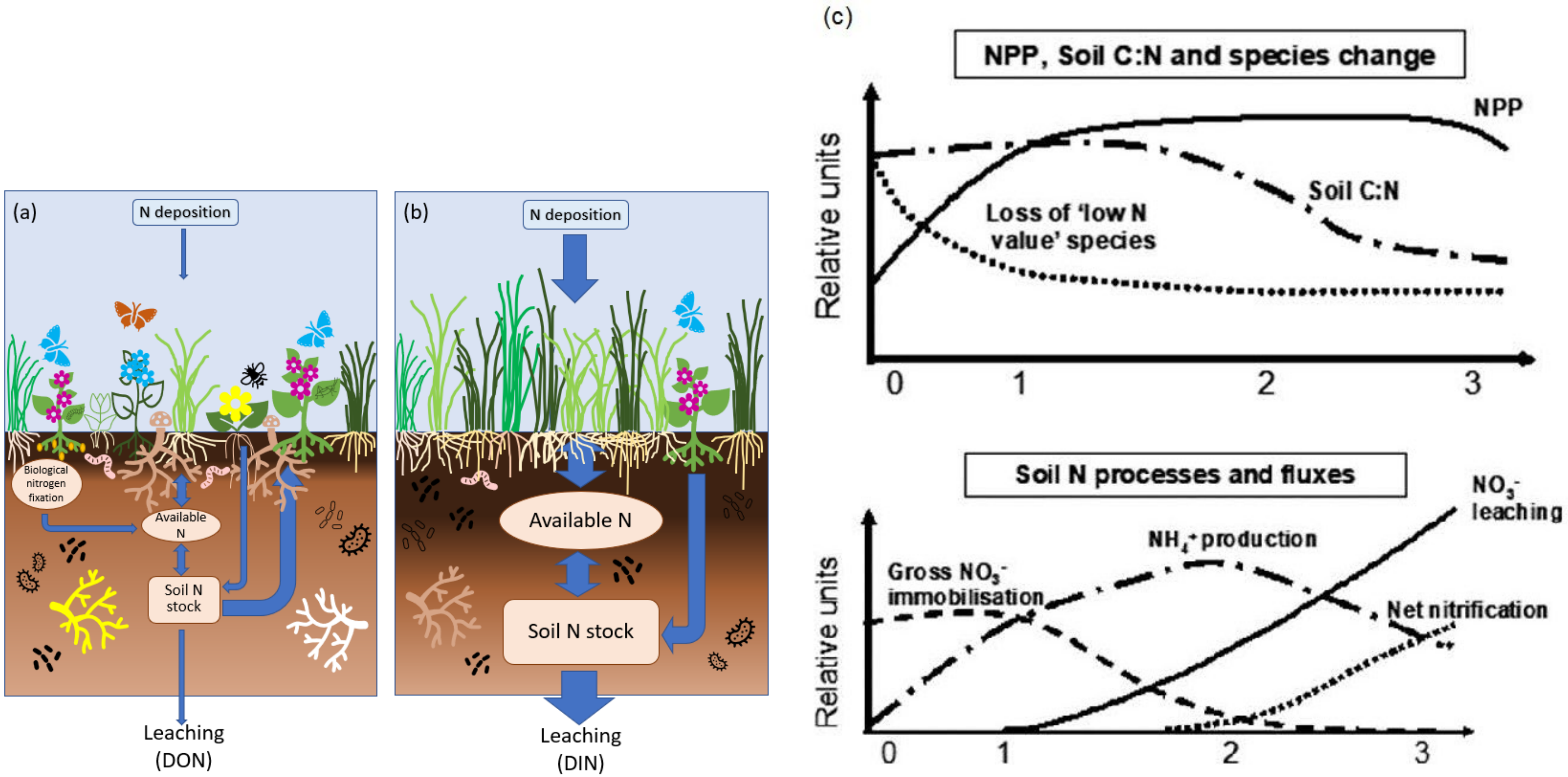


Figure 1: Typical changes in biodiversity and nitrogen (N) stocks and flows associated with N deposition: (a) in a system with rates of N deposition (relatively) unaffected by anthropogenic pollution. (b) when anthropogenic pressures increase the amount of deposited N to the system, (c) shows stages of ecosystem saturation (Emmett 2007), where NPP refers to net primary productivity.

1.2 The Air Pollution Recovery Indicators Project: Scoping Phase

The Air Pollution Recovery Indicators (APRI) project aims to fill the knowledge gap on timescales and processes of recovery by delivering new scientific research focused on indicators of ecosystem recovery from N pollution, including component animal, plant, and fungal species. In APRI Phase 1, heathland recovery was assessed at the site of a previous N addition experiment, particularly in terms of the below-ground ecosystem. Further studies will be needed to understand recovery of different elements of ecosystems and in different habitats. JNCC and UKCEH organised a workshop in Kew Gardens, 7–8 November 2023, to help to scope Phase 2 of the APRI project and to further understanding of ecosystem recovery. Here we report on the workshop and follow-up discussion.

Our report aims to aid the development of an indicator or set of indicators to allow understanding of ecosystem recovery, including but not limited to component species, in response to policies to reduce atmospheric pollution, specifically nitrogen (N). It considers the habitats to which indicators could be applied, and what sort of evidence may be useful to consider in developing a framework for Phase 2.

The report includes:

- The **policy context**.
- Reflections on the meaning of **recovery** and implications for desired recovery indicator trajectories.
- **Criteria for prioritising recovery indicators, habitats and species**.
- **Study approaches for assessing recovery**, assessing strengths and weaknesses.
- **Identification of potential recovery indicators,** including those that have already been used to assess N impacts and potential novel indicators.
- **Potential measurement methods** for different indicators, including interim assessment of cost.
- Interim assessments of **existing survey networks / projects** and **existing experiments** that could provide evidence for pollution recovery.
- **Key habitats** for which recovery indicators are needed.
- Advice on **knowledge gaps and future evidence requirements**.

Phase 2 projects will require further foundational work to confirm a priority indicator list; develop the database of available data, sites, and habitats; and undertake a gap analysis to identify additional priorities whether in data collection, habitats and/or indicator development. This foundational work would benefit from cross-community and international perspectives, to ensure it remains scientifically rigorous whilst being relevant for UK policy development.

2. The Policy Context

Many UK and international policies are in place to reduce N emissions and the impacts of N on the environment. There are also policies to halt and reverse biodiversity loss however these do not always explicitly account for pressures such as air pollution. As a result, there is a requirement to understand the potential for habitat recovery from N pollution across the UK, as this will greatly impact the delivery and timeframes of air pollution and biodiversity policy targets. For instance, the long-term objective of the Gothenburg Protocol is to reduce emissions of the pollutants which impact human health and habitats, and to ensure that N deposition to the environment does not exceed critical loads, by taking a stepwise approach considering advances in scientific knowledge. Ecological processes that can take decades or even centuries are relied upon for habitats to recover fully from the damaging nitrogen they have received. Interim indicators that have dynamics deemed as positive (i.e. desirable) may help policy makers to observe short-term beneficial changes that can encourage the further uptake of remedial measures (e.g. appropriate management or emission reductions). When used alone, long-term commitments can unintentionally discourage behavioural change by seeming impossible to meet, or they can result in the deprioritisation of investment when competing with more visible or immediate policy challenges. Below, we explore how the understanding of ecosystem recovery from air pollution intersects with international and UK policies and regulations, whilst outlining the possible outcomes for policy makers, conservation organisations, and developers.

Emission reduction commitments set out in the National Emission Ceilings Regulations (SI 2018/129), require a 16% reduction in ammonia (NH_3) and 73% reduction in nitrogen oxides (NOx) emissions by 2030 compared to 2005 levels. These commitments have driven policies and measures to reduce air pollution and its impacts. Additionally, the UK's biodiversity commitments and ambitions have been a key driver for understanding recovery pathways. For instance, there are ambitions in the 25 Year Environment Plan to restore 75% of one million hectares of terrestrial and freshwater protected sites to favourable condition and securing their wildlife value in the long term. These goals would complement international commitments through the Convention of Biological Diversity and the Global Biodiversity Framework. Together, these policies reinforce the need for organisations tasked with protecting the environment to understand what pathways of recovery are observable from declining pollution pressures. The commitments themselves are those prescribed by the Gothenburg Protocol within the United Nations Economic Commission on Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP). CLRTAP aims to protect ecosystems from acidification and eutrophication caused by transboundary pollutants and sets national emission reduction commitments as well as values at which deleterious effects are apparent (critical levels and critical loads).

As party to the Air Convention under the UNECE, Defra applies the critical levels and loads of specific pollutants to determine the impacts on the UK environment through the Air Pollution Trends Report (the latest being Rowe *et al.* (2023)). As we explore below, these critical levels and loads can also be used to inform our understanding of recovery. Critical *loads* for N pollution are defined as the rate of acid or nitrogen deposition, below which significant harmful effects are not expected to occur in sensitive habitats (Nilsson & Grennfelt 1988). Critical *levels* are concentrations of pollutants in the atmosphere, above which direct adverse effects may occur according to present knowledge (ICP Vegetation 2017). These set out clear deposition and concentration values to determine when harmful effects will occur to ecosystems, although they are regularly revised to account for new scientific understanding of the complex and emergent system responses to air pollution pressures. For instance, empirical critical loads for N deposition were revised in 2022 (Bobbink *et al.* 2022) and ammonia critical levels in 2023 (Franzaring & Kösler 2023), with an ongoing review for NOx. Assuming the critical loads and levels are a reasonable indication of when deleterious impacts occur, then dropping below those values would be expected to lead to habitat recovery. However, given the inherent uncertainty regarding the values themselves, and due to the complex behaviour of ecosystems, some signs of recovery may occur even if pollution remains above the critical load and/or level. Recovery may also be apparent even if the critical load was not exceeded, for instance due to lagged dynamics ('hysteresis').

If the emissions reduction commitments above are achieved, the amount of N entering the UK environment via the atmosphere will decrease. However, for the reasons briefly touched upon above, the level of ecosystem and species recovery to expect and the rate at which this will happen is unclear. This is exacerbated by the fact that the emission reduction commitments have no spatial element. The Nitrogen Futures report (Dragosits *et al.* 2020) recommended a 2-pronged approach to maximise impact improvements - combining UK-wide and locally targeted measures to maximise benefit of emission reductions measures in locations near affected habitats to aid wildlife and the recovery of semi-natural ecosystems of conservation importance. However, most of the UK exceeds (and has long exceeded) both critical levels and loads including in most Special Areas of Conservation (SACs), Special Protected Areas (SPAs) and Areas and/or Sites of Special Scientific Interest (A/SSSIs) (Rowe *et al.* 2023). Whilst on the trajectory to getting below critical load and level, it is important to track progress. Recovery indicators are one mechanism to do this and can help understand the potential for beneficial changes when getting closer to the critical load. Understanding how habitat recovery is linked to decreasing national N emissions will also assist in planning decisions, by demonstrating how and where emission reductions are making progress for nature.

Additional policy drivers underscore the need to develop recovery indicators. The UK Clean Air Strategy (2019) sets out clear actions to reduce NH_3 emissions and N deposition to sensitive habitats, which includes new rules on emission practices and fertiliser regulation through the 25 Year Environment Plan. The Clean Air Strategy includes a target 'to reduce damaging deposition of reactive forms of nitrogen by 17% over England's protected priority sensitive habitats by 2030', and since 2020 this spatially targeted metric has been included in the annual Air Pollution Trends Report (e.g. Rowe *et al.* 2023). The 25 Year Environment Plan commits the UK Government to restore 75% of the area of protected sites in England to favourable condition by 2042 This commitment requires significant emphasis on understanding habitat recovery pathways from N pollution, and effective N management in the right locations to benefit protected areas. If air pollution pressure on protected areas and the wider landscape is not addressed, biodiversity targets will likely be difficult to meet. Support to enable Local Planning Authorities to have a detailed understanding of emissions, impacts and recovery is also needed so they may deliver upon their duties, not only in relation to planning but also for Local Nature Recovery Strategies and other biodiversity policy responses. UK level projects, such as the UK Air Pollution Assessment Service (https://jncc.gov.uk/our-work/uk-air-pollution-assessment-service/), aim to address this need and facilitate decision-making to reduce emissions.

Pressures on ecosystems (e.g. land use, air and water pollution, climate change) are not routinely assessed quantitively in combination with each other. There is a clear need for in-combination assessments across sectors contributing pollutant emissions to inform policy in the future. It is also important for policy makers to have a firm understanding of N impacts and habitat recovery following decreases in N pressure, in order to monitor progress towards improvements in air quality that can protect ecosystems and help create the environmental conditions needed for nature recovery. Current methods to assess habitat condition (e.g. the Common Standards Monitoring guidance) were not designed to detect air pollution impacts, which may contribute to this pressure being overlooked. However, methods do exist to assess whether given amounts of N deposition may lead to a risk of harm to habitats, e.g. the Nitrogen Decision Framework (NDF) (Jones *et al.* 2016). The purpose of the NDF is to frame detrimental N impacts. If clear, agreed, and standardised metrics for recovery from nitrogen deposition are to be incorporated in impacts (risk) assessments and statutory habitat condition monitoring in the UK, it will be necessary to track incremental progress. It should be a priority for competent authorities, advisers, and professional bodies to develop and formalise the known effective scientific methodologies that can identify ecosystem recovery from damaging N pollution.

3. What do we mean by recovery?

Societal responses to anthropogenic pressure on nature have emphasised the preservation or conservation of relatively unmodified examples of ecosystems. With the recognition that many ecosystems globally have an extensive history of influence from human management, even in so-called wilderness areas, increasing emphasis has been placed on preserving long-standing interactions between people and nature. Nevertheless, there is a common assumption that a return to the original or baseline condition is desirable. There are two main challenges to this preservationist approach: the difficulty of determining what should be considered as the baseline or 'original' condition, and the need to account for environmental change.

Baseline conditions are often assumed to be those under traditional management, i.e. before the widespread adoption of mechanisation and fertiliser application. Habitats are defined and classified according to examples from nature reserves and other sites where management has not changed radically. Habitat descriptions from the National Vegetation Classification (NVC) (Rodwell 1992; Rodwell *et al.* 1992, 1992, 1995, 2000) could be used to define a baseline and/or a target for recovery, though it should be recognised that the habitat descriptions were compiled during an era of environmental damage, and some descriptions may provide a better indication of a 'baseline' than others. The JNCC Common Standards Monitoring (CSM) guidance (JNCC 2022) could then be applied to assess the degree of recovery. The response of different habitats within the CSM guidance to N deposition were reviewed in the context of the development of the NDF (Jones *et al.* 2016).

The NVC and CSM guidance are clearly related to the condition of habitats in the past. The vegetation history of Britain (and Ireland) has been extensively discussed and studied, notably through analysis of pollen grains (palynology), and to a lesser extent the analysis of macro- and micro-fossils. While these records show extensive areas of tall forest during the Holocene, open habitats (grasslands, heaths, mires, bare rock, etc.) have also been widespread throughout the period. Indeed, much of the UK vascular plant flora is restricted to non-woodland habitats. There is thus a good case for maintaining a diversity of habitats across the UK. As well as being informed by the past, this diversity of habitats can help maintain a portfolio of options for system resilience regarding climate change and other environmental alterations (Oliver *et al.* 2015).

Climate change due to anthropogenic greenhouse gas (GHG) emissions is now an accepted fact (IPCC 2023). It is apparent that Earth will not be returning to a pre-industrial climate on any foreseeable timescale. Nitrogen pollution has effects on GHG emissions, potentially increasing the capture of carbon dioxide, although experimental data show a smaller increase in capture than modelling studies suggest (Schulte-Uebbing *et al.* 2022). Atmospheric N pollution is also likely to increase production of N_2O, a potent greenhouse gas (Yang *et al.* 2021). However, the focus of this study is on N effects on ecosystems, and the additional effects of climate change are relevant. When all habitats are on a trajectory towards higher temperatures and more climate variability, what should conservation (or restoration) targets be? Despite accepting that some species assemblage change will be a necessary outcome of climate change, under a future climate a less polluted ecosystem will have lower biodiversity loss than a more polluted system due to the underlying mechanisms associated with community change in response to N pollution (e.g. Hautier, Niklaus, and Hector 2009). Some studies have run future simulations of climate change with and without N pollution, to define the target species assemblage (e.g. McDonnell *et al.* 2018). It is not easy to predict the speed with which climate will change, and at what point it might stabilise. Defining conservation targets in a changing world remains a considerable challenge, and a necessary one to address, to allow the measurement of progress (Gann *et al.* 2019).

In the case of recovery from air pollution, such a clear goal may not necessarily be required. Instead, there is a need to understand how to steer emissions reductions policies by being able to measure interim progress. For quantifying interim progress, we do need to know the direction of change in an indicator that will indicate recovery. **What is important is to identify an indicator or set of indicators that can indicate recovery from air pollution (specifically N deposition), in as unequivocal a manner as possible given other environmental changes.**

Pathways of recovery can be in relation to biodiversity (e.g. species composition, indicator species presence) and/or ecosystem function (e.g. soil properties) (Figure 2), and the timescale of their responses may differ. Such system elements could be candidate indicators. Pathways of recovery may differ from pathways of impact of N pollution, thus exhibiting hysteresis (Meyer *et al.* 2023; Payne *et al.* 2017), especially given the importance of cumulative pollution in determining system responses (Duprè *et al.* 2010; Bernhardt-Römermann *et al.* 2015). As shown in systems that can get 'stuck' with undesirable dynamics, it is not always clear what we can recover to, and with how much investment (Hobbs, Higgs & Harris 2009).

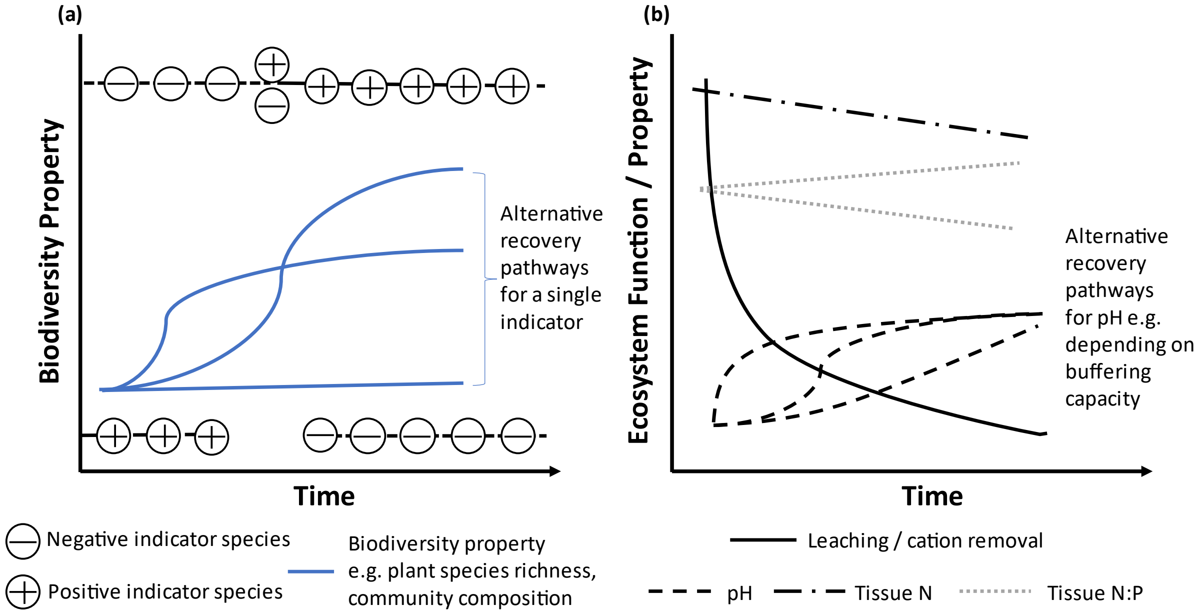


Figure 2: Putative recovery pathways over time as N deposition declines for (a) biodiversity and (b) ecosystem functions/soil chemical properties.

The presentation of what is possible and/or desirable regarding pollution recovery is beyond the scope of this report; indeed, this is a political and societal decision. Instead, the remainder of the report considers how we might prioritise among different possible indicators of system recovery from N pollution, what study approaches can provide evidence of recovery, what indicators have previously been used to assess impacts of N pollution (with associated properties) and whether these may offer opportunities to assess recovery in the light of ongoing environmental change. We will also consider the use of novel indicators. Throughout, we present what is theoretically possible, prior to emphasising what future directions would be most desirable given the status of current projects and available evidence to enable APRI Phase 2.

4. Criteria for Selecting Indicator, Habitat and Species Priorities

Resources are limited and there is an urgent need to understand the timescales and extent of ecosystem recovery, so the indicators used to assess recovery need to be prioritised, as do the habitats, ecosystems, and species to be considered. There may be trade-offs between the cost of measuring an indicator (or collection of indicators) and its (their) suitability to indicate recovery. Indicators may also exhibit responses at different points along a recovery pathway. Reviews of indicators of N pressure and impacts (e.g. Rowe *et al.* 2020) provide useful context, but different considerations may apply to recovery indicators.

It is desirable that **indicators** have one or more of the following properties:

1. Specificity to declining N pollution. This determines the degree to which the N signal can be separated from other factors.
2. Speed of response to declining N pollution. This enables rapid understanding of whether policy is having an impact, bearing in mind that indicators that respond slowly may still be useful.
3. Sensitivity of response to N. For example, does the indicator respond to small reductions in N regardless of the former pollution load?
4. Generality to multiple habitats. Or whether it can only be used for a specific habitat.
5. Relatedness to recovery endpoints, potentially including Favourable Conservation Status. For example, if species composition is of ultimate interest, then a biodiversity metric may be useful even if it responds slowly.
6. Previous use to indicate N impact. This potentially allows the use of historic data. Such data may need to cover multiple sites and/or habitats to help inform understanding of system responses to policy; data from a single site may be useful for further studies on that site and to inform scientific progress.
7. A large range of pollution over which the indicator has been assessed. This enables understanding of likely recovery from different pollutant ‘starting’ points.
8. Potential added value to inform other policy areas, e.g. carbon sequestration, water quality, flood risk.
9. Resilience in the face of other anticipated changes. For example, would an indicator based on the same species be applicable after climate change?
10. Feasibility of cost-effective collection. For any given indicator, this depends on the collection method.
11. Measurement uncertainty. This explores the degree to which measurement method represents the ‘true’ value of the indicator. For instance, a chemical assay may measure tissue N fairly precisely, whereas remote sensing may provide only an approximate value of tissue N.

There may be additional properties that can be considered. For instance, van Strien *et al.* (2012) discuss desirable mathematical properties, such as monotonicity and proportionality, for indicators of biodiversity recovery. Rowe *et al.* (2017) recommended indicators that respond positively to improved conditions, e.g. forb/total cover ratio rather than grass/forb cover ratio.

For *habitat and/or ecosystem* prioritisation, there may be a need to understand how rare or threatened these properties are in a national and/or international context (which may be aided by Red Lists), where there are gaps in our understanding, and the policy and funding priorities of JNCC and the other Statutory Nature Conservation Bodies (SNCBs), Defra and the devolved administrations.

Species occupy an interesting space in these criteria; they may both be a potential indicator and an organism that is a focus of legislation and/or policy. Prioritisation of species may therefore need to take both aspects into account – clearly a species that has a high specificity in response to declining N and is a focus of policy action may have a higher priority to be included than one that is of limited policy interest and has low N specificity. This statement is tempered by ideas around naturally functioning systems and more holistic approaches that may mean a species remains important to consider from that standpoint even if it is not useful as an indicator of pollution recovery. A species that has high specificity in response to N may be prioritised on the indicator list, regardless of whether it is of interest in and of itself to policy. If a species is used as a biogeochemical indicator, for example of moss tissue N, it is desirable that it occurs throughout the environmental gradient being assayed. If a species is used to indicate biodiversity value, presence along the gradient is not required.

Prioritisation may also need to consider the uncertainty of information regarding indicators, especially the nature of their response to declining N, and/or in relation to how precisely the measured value represents the desired indicator. In addition, and as explored further in the Recovery Indicators section, it may be necessary to consider a basket of indicators (which may vary by habitat type). Thus, the type of indicator (e.g. pressure, response (biogeochemical or biotic) and/or derived indicators such as critical level/load exceedance or ecosystem service value; see also Table 2) may feed into the prioritisation process. Including at least one of each type of indicator within a basket would help achieve balance and allow the inclusion of indicators that score highly in relation to different criteria. In other words, it must be recognised that a single 'ideal' indicator likely does not exist, thus compromises and a weight-of-evidence approach will likely be required.

The direction of change for a given recovery indicator is not necessarily consistent (see also Figure 2). This may be an additional facet when considering which indicators to prioritise. For instance, it might be expected that as N declines, foliar nitrogen: phosphorus (N:P) ratio will also decrease due to greater N limitation (see e.g. Krüger I *et al.* 2020). However, in some circumstances a decreased N:P ratio can arise from *greater* N supply, presumably due to increased release of phosphatases that enhance P uptake (Rowe *et al.* 2008). Another example is soil total C:N ratio, which generally decreases as extra N is immobilised into the organic matter and potentially increases the rate of carbon (C) mineralisation. However, in soils with low organic matter content, additional N can lead to an increase in soil total C:N, due to the stimulation of plant growth and increased production of fresh litter with a high C:N ratio (Jones *et al.* 2004). Thus, those indicators that can potentially respond in both a positive and negative manner (bidirectionality) to declining N may become lower priorities than those indicators that only respond in one direction to declining N.

An additional criterion to account for may be the temporal scale at which ecosystems respond to environmental change, including decreasing pollution pressure. Thus, systems can have a direct response to environmental change (e.g. litter decomposition increasing when temperatures increase, providing sufficient moisture exists) which may occur on a relatively rapid timescale. There may also be an indirect response mediated by vegetation or microbial communities – this could exacerbate or dampen the direct response, depending on whether the biotic change reinforces or runs counter to the direct response (see the response-effect framework; Suding *et al.* 2008). For instance, if vegetation with more recalcitrant litter starts to dominate a site as temperature increases, the expected increase in decomposition may not materialise. Whether declining N pressure leads to such indirect as well as direct responses would need further investigation.

5. Potential Study Approaches for Obtaining Evidence of Recovery

Critically, evidence for recovery can only be obtained from locations where N pollution has decreased. Suitable locations include:

- Areas where N pollution pressure has decreased or will decrease, e.g. due to an emissions source closing, or due to policy measures (e.g. van Strien *et al.* 2018).
- Experimental plots where previous N additions have decreased or ceased (e.g. Strengbom *et al.* 2001).
- Experimental plots where atmospheric N deposition is artificially decreased, e.g. by installing a roof to intercept rainfall and substituting a solution containing less N (e.g. Beier *et al.* 1998).
- Experimental mesocosms, i.e. parts of an ecosystem removed into a controlled setting where N pollution pressure can be decreased (e.g. Britton *et al.* 2019).

A range of study approaches have been used to assess the damaging **impacts** of atmospheric N pollution on ecosystems, such as spatial gradient surveys, resurveys, and experiments (Table 1). With an initial focus on experimentation, revisions to the empirical critical load for nitrogen increasingly consider evidence from gradient studies and resurveys (Bobbink *et al.* 2022).

The same approaches could prove relevant for understanding **recovery** trajectories. In general, survey approaches allow evidence to be obtained over a broad range of environmental conditions but can make it hard to separate the effects of N pollution from other factors. By contrast, experimental approaches, if properly replicated and randomised, can isolate the effect of a single factor. However, an experiment at a single location or a limited set of locations may not represent how ecosystems respond under different environmental conditions. Similarly, plot-based or mesocosm experiments might not reflect real world responses where landscape scale processes are in play (e.g. dispersal, etc). An intermediate approach is to use a ‘multi-site experiment’, with one experimental contrast (or a small number of contrasts) repeated at a number of locations. Modelling studies can also provide useful insights although they do not provide conclusive evidence for underlying processes.

The potential uses of these approaches to characterise recovery from N pollution are discussed in turn below; we note that whether recovery is to be expected or not may depend on whether N pollution declines to a value below or above the critical load. However, the uncertainty around critical loads and critical levels, together with the complex nature of ecosystem properties, especially hysteresis, means that recovery in indicators may happen above a critical load, or may not occur even were N pollution to drop below it. It is this knowledge that APRI Phase 2 can begin to uncover. As such, after considering the different methods, we provide a recommendation as to the most promising study approach(es) to adopt using currently available data or data that can be anticipated in the near future.

Table 1. Qualitative properties of different current and potential methodological approaches to investigate N deposition effects which may be used to understand recovery. The table presents different descriptors associated with each of the methods, which highlight the trade-offs among approaches e.g. realism vs ability to assign cause. Reproduced from Table A1 in Perring *et al.* (2018), a manuscript which focussed on forest understorey communities. The comparison generally holds for other ecosystems. However, globally distributed experiments on nutrient impacts exist for grasslands – NutNet – and have an associated timescale (see Borer *et al.* 2014).

	Experiments			**Spatial gradient**			**Time series (re-survey s.l.)**				
Property	**Laboratory experiment** Greenhouse or mesocosm experiment	**Field experiment** Local to regional field experiments	**Globally distributed experiment** International to global field experiments	**Local gradient** Point source gradient	**Regional gradient** Different sites across a landscape	**(Inter)-National gradient** Networks / National inventory database	**Monitoring and permanent plots** Marked plots	**Quasi-permanent plots** Same site	**'Non-permanent' plots** Same region	**Combination of spatial & temporal study / Meta-analyses**	**Simulation Modelling**
Time scale	Predominantly short-term	Predominantly short-term	Not existing	Not applicable	Not applicable	Not applicable	Varying	Long term	Long term	Mostly short-term	Potentially unlimited
Confounding variables	None	Ideally none	Likely	Possible	Likely	Likely	Likely	Likely	Likely	Potential to be controlled	Can be controlled
Environmental data	Available	Available	Potentially available	Available	Available	Available	Sometimes available, particularly recently	Sometimes available	Not available for precise plot locations	Sometimes available	Depending on what required for model input
Causal interpretation	Possible	Possible	Possible	Possible if no confounding variables	Difficult without other sources of information e.g. Ellenberg values in Europe, modelling	Difficult without other sources of information	Possible if no confounding variables	Difficult without other sources of information	Difficult without other sources of information	Possible	Possible

	Experiments			**Spatial gradient**			**Time series (re-survey s.l.)**				
Property	**Laboratory experiment** Greenhouse or mesocosm experiment	**Field experiment** Local to regional field experiments	**Globally distributed experiment** International to global field experiments	**Local gradient** Point source gradient	**Regional gradient** Different sites across a landscape	**(Inter)-National gradient** Networks / National inventory database	**Monitoring and permanent plots** Marked plots	**Quasi-permanent plots** Same site	**'Non-permanent' plots** Same region	**Combination of spatial & temporal study / Meta-analyses**	**Simulation Modelling**
Realism	Low	Dependent on design	Dependent on design	High	High	High	High	High	Moderate	High for combined approaches	Dependent on model set-up and aim
Data availability	Moderate to High	Moderate to High	None	Potentially high	Potentially high	Potentially high	High	Moderate	High	Moderate	Dependent on model set-up and aim
Reliability of results	High	High	High	High	High	High	High	Moderate	Moderate to low	Moderate to high	Dependent on model aim and validation
Spatial coverage	Limited	Often limited	High	Limited	High	High	Limited	Moderate	Often high	Potentially high	Potentially unlimited

5.1. Surveys and Gradient Studies

Spatial data on pollution trends could be used to find sites with declining N pressure and compare these sites to ones where there have not been the same pollutant declines. This is essentially a survey approach, so additional factors would need to be accounted for. To provide power to detect recovery from declining N would likely require a large number of locations. Targeting of sites could take advantage of (i) Existing Survey Networks, such as the use of Countryside Survey data, (ii) sites where attempts are being made to decrease diffuse pollution e.g. Shared Nitrogen Action Plan landscapes, or (iii) the closure of point sources, potentially aided through Environment Agency / other regulator data. The latter, in particular, offers the opportunity for additional experimental approaches to understand recovery, detailed further below. Resurveys across gradients can also provide insight to recovery pathways where N deposition has declined, allowing comparison across space *and* time. This approach provides an increase in comprehensiveness and representativeness in comparison to resurveys at single sites (Verheyen *et al.* 2016).

A related approach to understanding recovery trajectories from declining N deposition pressures could be through consideration of the neighbouring land use and the spatial gradient in pollution pressure. For instance, where heathland is the target habitat, heaths surrounded by agricultural land where the intensity of use has been declining could be compared with heaths where the surrounding agricultural land use intensity has remained high. Agricultural land use intensity is related to ammonia (NH_3) emissions; other N-containing pollutants, e.g. nitrogen oxides (NOx), need also to be considered since these may not have changed and thus may obscure the presumed decline.

Whatever the approach, it is crucial that the N pressure to the systems is estimated, preferably through empirical measurements and, where possible, taking advantage of existing networks (e.g. the United Kingdom Eutrophying and Acidifying Pollutants (UKEAP) Network). Modelled estimates of ammonia concentration and/or N deposition can also be used. Confidence in such model estimates would be increased if monitoring data verify the declines, at least at some sites. It would be helpful to have estimates of historical N deposition pressure, as well as current and future N pollution dynamics, given the links between cumulative N deposition and biodiversity responses (Duprè *et al.* 2010; Bernhardt-Römermann *et al.* 2015). Spatial projections of N deposition under different future development scenarios are available (Dragosits *et al.* 2020), although these are highly uncertain. At present, spatially explicit estimates of historical concentration and deposition are also uncertain, so there may not be enough certainty about which areas have experienced declines in N pollution for large-scale spatial analyses to be a viable option in practice.

5.2. Intensive Experiments

Experimental additions of N have provided robust evidence for pollution impacts (see examples in Bobbink *et al.* 2022). Under the UKREATE consortium (Eutrophication and Acidification of Terrestrial Ecosystems in the UK) research programme, N was applied experimentally (in various forms and in combination with other treatments) to different habitats across the UK. These sites are described in detail in the Existing Experiments section below. Many experiments were discontinued in the early 2010s, and there is potential to use these sites to examine how cessation of N addition has changed potential indicators. The inclusion of control plots, and the high quality of existing data, make these experiments a key resource.

Some previous experiments (e.g. Gardsjon, see Moldan *et al.* 2004) also included rain-replacement treatments, in which rainfall was diverted using roofs and replaced with an equivalent solution with less N. If this can be done without methodological artefacts (e.g. controlling for the impact of the roofs or minimising their impact by automatically retracting them when it is dry), the approach can provide good evidence for the effect of decreasing (wet) N deposition.

New intensive experiments could be set up to investigate system responses to declining N pressure, with different levels of N decline. This may involve a combination of laboratory and field experiments, the former helping understand mechanisms of response. Such experiments could consider methods adopted in Phase 1 of APRI, to increase comparability.

With any experimental N additions, care needs to be taken that the amount and duration of exposure reflects the pressure from pollution. In experiments that mimic N deposition, the N dose, solution concentration, and frequency of exposure should as far as practicable be comparable with atmospheric deposition. Background levels of N deposition, and their change, need to be accounted for in any field experiments. In experiments that mimic exposure to gaseous ammonia (or other N gases) the gas release regime must be carefully designed to represent real world concentrations and conditions, such as at Whim Bog over a peatland (Leith *et al.* 2004) and Glencorse within a woodland (Deshpande *et al.* 2024). Care is also required when estimating the effect of a change in the atmospheric ammonia concentration on the N deposition rate to the ecosystem, due to the complexity of the bi-directional exchange of ammonia with surfaces. Deposition can be measured indirectly using eddy-covariance and co-located ammonia monitoring; however, this is costly and gives an average over a large area of land that is less suited to understand ecosystem and species changes over a gradient, or to individual species. Estimations of deposition can therefore be derived using bi-directional resistance modelling (e.g. Nemitz, Milford & Sutton 2001), with methodology covered in detail for Whim Bog (Jones *et al.* 2007; Cape *et al.* 2008) and Glencorse (Deshpande *et al.* 2024).

5.3. Multi-site Experiments

Relatively simple experiments can still be informative, particularly when repeated across multiple locations. For example, comparison of N addition versus no N addition, repeated across several locations where N is otherwise known to be declining (see below), would give opportunities to understand changes due to N pollution decline in multiple environmental contexts. Such experiments could be established at relatively low cost and can give high-quality evidence if attention is paid to experimental design principles such as random treatment allocation and careful collection of contextual data. Some studies have established more involved experiments at one or multiple locations (e.g. Blondeel *et al.* 2020; Borer *et al.* 2014).

5.4. Exploiting closures of point sources

There are opportunities to set up innovative experiments to take advantage of the closure of point sources of N emissions and add value to what would otherwise be a survey design. It would be helpful for closures or reduction through variations to be monitored and nearby ecosystem responses tracked. Time-series, found-experiment and fully experimental approaches could be applied in these locations.

By recording **time-series** of ecosystem properties at locations where N is known to be declining, the recovery of elements of the ecosystem may be detected. This approach has been applied at broad scales to detect the effects of pollution decline, for example the recovery of pH in UK soils due to decreased acid rain (Reynolds *et al.* 2013). Ecosystem recovery following closure of a farm at Moninea Bog, Northern Ireland, allowed tracking of ecosystem recovery from ammonia impacts (Sutton *et al.* 2020). However, there are no known studies that have monitored recovery from simultaneous reductions in NH_3, NH_4^+ and NO_3^- (Sutton *et al.* 2020). Monitoring could be targeted at locations where a dramatic decline in total N pollution is expected, and further data needed to understand recovery across habitats/species. A more detailed understanding of where key sources are, at local scales (e.g. less than 1 km), would assist with identification of these ‘found experiments’ with reduced pressure from ammonia concentration or nitrogen deposition.

An example of a **found experiment** approach is to find paired locations near point sources of emissions, some of which are closed (or about to close) and others which will remain open. If distributed pairs of ‘open’ and ‘closed’ sites can be found, across a range of environmental conditions, then system responses to declining N can be isolated, and potentially understood in relation to contextual variables. As with other approaches, a good understanding of background N levels would also be needed, as some N deposition would continue to any focal site, regardless of the closure of point sources. Finding matched pairs of sites is not straightforward, and as with gradient approaches, the fact that sites may differ in more ways than air pollution pressure can make it hard to separate the effects of other factors.

In a **fully experimental** approach, N deposition treatments are allocated at random to pre-identified plots, to control for other factors. An experiment could be initiated such that some plots at different distances away from the emission source (preferably in several directions given variability in wind direction) could continue to receive an N dose while other plots, also at a range of distances and directions, do not. Provided treatments are allocated at random, recovery dynamics in response to declines in N pollution could be separated from other factors (e.g. climate changes).

In all these approaches, caution must be exercised when scaling up from plot-scale results to landscape scale expectations.

5.5. Simulation Modelling

Simulation modelling is included as the final column in Table 1. This provides another means to understand and potentially predict the impacts of declining N pressure on systems and relevant indicators. The workshop discussed how simulations with and without declining atmospheric N pollution pressures, run in conjunction with projected climate change and other stressors, could help project the trajectory of response-based recovery indicators. Such projections could be ground-truthed through subsequent monitoring. Simulation modelling needs sufficient and suitable observation data to be reliable.

5.6. Summary: Study approaches to recovery – theory versus practice

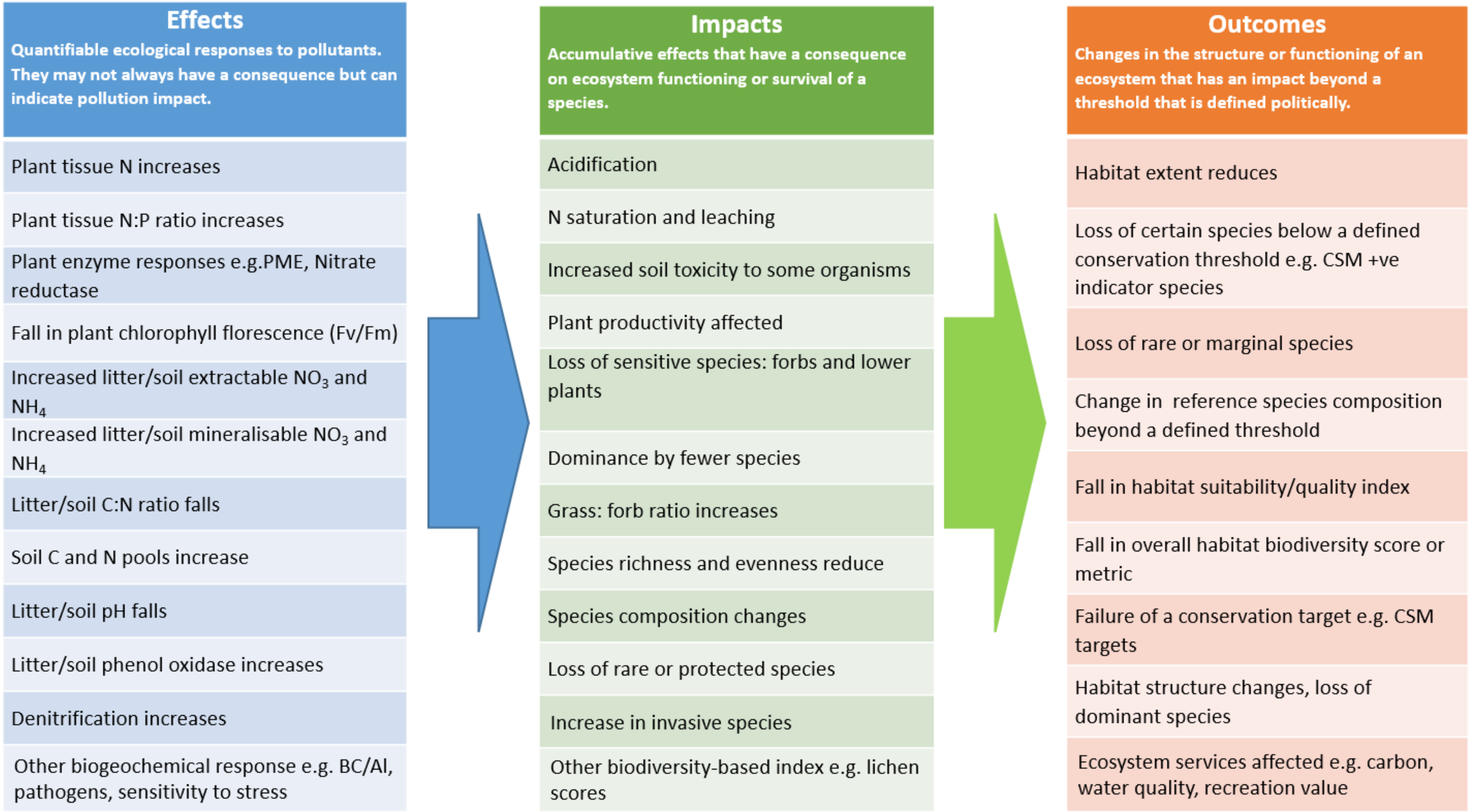
Different study approaches to understand recovery from N deposition have variable strengths and weaknesses. All the approaches discussed above can, in theory, provide evidence in relation to indicator responses to declining N pollution. However, in practice, only some of them are feasible within the UK landscape, given current data availability and N deposition trends. In our opinion, the two most feasible options are to (a) exploit existing N impact experiments where N additions have been discontinued; and (b) exploit the closure of point-sources of emissions by establishing, at minimum, a time-series of ecosystem properties. Preferably, (b) would be extended to encompass found-experiments or full experimental approaches to isolate N recovery trajectories. With any adopted approach, the actual decline in N pollution pressure should be monitored. If there are advances in the understanding and mapping of historical N pollution pressures, large-scale studies could be considered to help understand how landscape processes affect recovery from N deposition, providing confounding variables can be controlled for. It is for this reason that large-scale survey approaches are not recommended as a focal area within the timeframe of the APRI Phase 2 project, even if e.g. biodiversity surveys at the local scale may be used within options a) and b). We do not recommend broader-scale surveys given APRI Phase 2 aim is to understand potential indicators of recovery from N pollution; for example, **unequivocal** decline in N pollution is needed to assess ecosystem response to this decline, and thus establish potential indicators that could be used more widely in subsequent years.

6. Recovery Indicators

6.1. Recovery Indicator Categorisation

To aid prioritisation and decide upon a relevant basket of recovery indicators, it can be useful to consider their properties in relation to different categories in the chain of ecosystem recovery such as effects of N and resulting consequences (e.g. impacts of N and outcomes for the ecosystem). **We provide a preliminary assessment of potential indicators against different categories (Table 2) but recommend that further work is carried out to finalise this list.** This is especially pertinent to those categories that could be very important in determining a recommendation for eventual prioritisation of indicators to assess, but that are currently lacking value inputs in some table cells. For instance, this includes the specificity and/or sensitivity in indicator responses to declining N pressure.

A key distinction is whether a given recovery indicator relates to the **pressure** from air pollution (e.g. atmospheric concentration or deposition load) or is indicative of the **response** of the ecosystem. Responses can be split into biogeochemical or biotic, whether plants, lichens, microbes, or fauna, and at the individual, population, or community level (including metrics such as species richness, composition, evenness, and functional diversity). Rowe *et al.* (2017) suggest that biogeochemical and biotic response metrics can mainly be understood as *midpoint* and *endpoint metrics,* respectively, although some species responses could be seen as midpoint indicators. Endpoint metrics reflect outcomes directly relevant to people. Other methods of splitting responses, originally regarding N impacts, include Effects, Impacts and Outcomes (Figure 3). Such a diagram can provide inspiration for a potential list of recovery indicators.



Effects

Quantifiable ecological responses to pollutants. They may not always have a consequence but can indicate pollution impact.

- Plant tissue N increases
- Plant tissue N:P ratio increases
- Plant enzyme responses e.g.PME, Nitrate reductase
- Fall in plant chlorophyll florescence (Fv/Fm)
- Increased litter/soil extractable NO_3 and NH_4
- Increased litter/soil mineralisable NO_3 and NH_4
- Litter/soil C:N ratio falls
- Soil C and N pools increase
- Litter/soil pH falls
- Litter/soil phenol oxidase increases
- Denitrification increases
- Other biogeochemical response e.g. BC/Al, pathogens, sensitivity to stress

Impacts

Accumulative effects that have a consequence on ecosystem functioning or survival of a species.

- Acidification
- N saturation and leaching
- Increased soil toxicity to some organisms
- Plant productivity affected
- Loss of sensitive species: forbs and lower plants
- Dominance by fewer species
- Grass: forb ratio increases
- Species richness and evenness reduce
- Species composition changes
- Loss of rare or protected species
- Increase in invasive species
- Other biodiversity-based index e.g. lichen scores

Outcomes

Changes in the structure or functioning of an ecosystem that has an impact beyond a threshold that is defined politically.

- Habitat extent reduces
- Loss of certain species below a defined conservation threshold e.g. CSM +ve indicator species
- Loss of rare or marginal species
- Change in reference species composition beyond a defined threshold
- Fall in habitat suitability/quality index
- Fall in overall habitat biodiversity score or metric
- Failure of a conservation target e.g. CSM targets
- Habitat structure changes, loss of dominant species
- Ecosystem services affected e.g. carbon, water quality, recreation value

Figure 3: Potential response indicators of Nitrogen impact (rather than recovery) split across Effects, Impacts and Outcomes categories. This provides a platform to consider a non-exhaustive list of potential recovery indicators, whose properties we outline in Table 2. Figure provided by Chris Field from his and others' work. PME = phosphomonoesterase, BC = base cations, Al = Aluminium, CSM = Common Standards Monitoring guidance.

Beyond the categorisation of recovery indicators in terms of pressure / biogeochemical response / biotic response, other categories can be important to consider. These categories mirror the points raised in relation to Criteria for Selecting Indicator, Habitat and Species Priorities. These include the specificity or sensitivity of response to N, especially if any response can also be attributed to policy action. Pressure indicators, particularly atmospheric concentrations, generally respond directly to declining N pollution. However, ecosystems are complex adaptive systems (Levin 1998), and indicators of ecosystem impacts, outcomes and effects are often less specifically related to declining N. Numerous other factors could affect recovery indicators, unless the dynamics are being considered in relation to a well-designed experiment with appropriate controls. This is why we recommend focusing APRI Phase 2 on those experiments where N addition has ceased, and otherwise consider using closure of point sources or variations in activity (where N decline is unequivocal) but coupled with experiments to help isolate the impacts of declining N.

Other important categories when selecting an indicator or set of indicators pertain to whether responses are relatively rapid (seconds to days), intermediate (months to years) or slow (decades or longer), and whether indicators are novel, or whether they have been used previously to indicate changes in N. Responses at all these timescales are of interest and indicators that have been used previously have benefits of continuity. For those with previous use, it is most likely that they have been employed to indicate increasing N – whether pressure or response. Given the potential for hysteresis in response (e.g. Meyer *et al.* 2023), it is not always clear whether this prior use will capture recovery from declining N pressure. However, the broader the use of a given indicator the more likely that single sites can be used to benchmark results with more confidence (see also Britton, Fielding & Pakeman 2023). However, the specificity or sensitivity to assess this may need accounting for (De Cáceres & Legendre 2009).

Using the presence or absence, or relative abundance of particular species, was also suggested as a means to indicate recovery. For instance, the identification of characteristic species of particular habitats that increase as N deposition decreases across a gradient or positive indicator species for high quality habitat (Rowe *et al.* 2016). However, species previously used to examine N impacts may not recover under declining N due to long-term feedback in the system including through competitive and litter-mediated dynamics with the species that replaced them when N increased (Meyer *et al.* 2023). Indeed, the Review of Transboundary Air Pollution (RoTAP) reached the conclusion that there are few reliable N indicator species, and those that there are may be too rare to be useful. More recent research has pointed to the need to combine groups of sites (De Cáceres, Legendre & Moretti 2010) and/or use species combinations (De Cáceres *et al.* 2012) to improve species indicator analysis. It will also be important, if indicator species are chosen, to not include species that are unlikely to reappear because of climate change and/or because they are poor dispersers, especially in fragmented landscapes. However, it is important that we recognise what has been lost.

Table 2 provides a list of potential indicators collated from workshop discussion and subsequent assessment of the literature, and their relevant properties according to some of the categories outlined above. Table 2 also highlights the importance of considering indicators that may not have worked previously, preventing wasted effort. This requires expert judgement, since publication bias typically highlights successful indicators, not ones that fail to perform. We recommend that this table is extended to consider as many criteria for prioritisation as possible, and to ensure indicators that are eventually chosen to represent a robust selection across timescales, ecosystem properties, and habitats.

6.2. Process Indicators versus Composition Indicators

When considering recovery indicators, it may also be useful to consider indicators that represent the processes and functions related to nitrogen (e.g. inorganic N leaching) as well as those that are 'endpoint' indicators (e.g. specific flora or fauna). Considering both also reflects the different timescales of response.

Given the uncertainty associated with biodiversity targets and environmental change, it may also be useful to consider specific functional measures rather than compositional end points. Functional measures relate to the trait distribution of the vegetation and not necessarily the taxonomic identity. For instance, increased N might be expected to decrease the role of N-fixing plants in the vegetation community; a recovery indicator could be the presence (or abundance) of N-fixing plants in the vegetation community, not necessarily the exact taxonomic identity of the N-fixer(s). Measuring abundance comes with its own challenges, and presence or absence may be faster and more feasible to assess but may not give as much insight into the recovery process – given other factors that may prevent recruitment. When considering N fixation, the level of gene expression as measured through RNA (ribonucleic acid) analysis could also be considered, to give an indication of fixation activity.

6.3. Indicator Baskets

The workshop discussed the need to consider a basket of indicators to signal recovery. Any choice will need to consider the remarks above, and likely cover a set of indicators that could respond relatively rapidly and those that respond more slowly, those that represent process as well as composition, and those that represent below- as well as above-ground responses. The workshop emphasized the desirability of measuring atmospheric concentrations at all sites and estimating deposition rates where possible. These amounts will to some extent determine the likelihood and extent of recovery, and such measurements will also improve modelled estimates going forward. Measurement methods for this aspect could vary and could involve active measurements, passive measurements with samplers, and even passive measurements through biomonitoring (cf. ICP Vegetation and their European moss survey). Biomonitoring could consider a scoring system for nitrophyte and acidophyte lichens, as a complement to bryophyte and vegetation surveys (Larsen *et al.* 2009; Davies *et al.* 2007).

Ideally, indicators should have a specificity in response to N. If indicators are not specific to N, then a weight-of-evidence approach could be used to infer recovery from nitrogen impacts, rather than a pass/fail of a particular metric (see Jones *et al.* (2018) as cited by Britton, Fielding & Pakeman 2023). In other words, a lack of precision for any given metric could be compensated by having multiple metrics. If multiple indicators that have some relationship to declining N pollution show signs of recovery, then this is stronger evidence for N recovery than a pass/fail of a single metric (see also the grading system suggested by Society of Ecological Restoration). Britton *et al.* (2023) further suggest that the choice of indicators within a basket [to indicate recovery] may be habitat specific.

It may be useful to include at least one indicator in any basket that would have public appeal, for instance butterflies. Having public appeal may help raise the profile of air pollution issues - such that it sits in the consciousness of the general public, much as the climate change crisis and to a lesser extent the biodiversity crisis do. Air pollution, after all, is regarded by the United Nations as the 'Third Environmental Crisis'.

Awakening the public consciousness may be aided by Massive Open Online Courses (MOOCs) – for instance, there are already courses on Nitrogen pollution and impacts in over 11 languages, including targeted training to individual threats. Such awakening also enables citizen-science like approaches to be adopted. This could also help encourage public and private investment in indicator development and tracking – for instance, a study in Western Australia linked up primary/secondary schools across the state with Australia Post and researchers at the University of Western Australia to understand soil biology in response to environmental conditions. In Scotland, the Mountain Heights, Hidden Depths project is working with hillwalkers to collect soil samples from three widespread habitats (moss heath, grassland, dwarf-shrub heath) on each of 270 Munros (mountains over 3,000 feet). Samples will be used to investigate soil biodiversity by eDNA methods, and soil C, N and pH data are also being collected to allow investigation of relationships between soil biodiversity and environmental drivers including air pollution (for more information see: https://munro-biodiversity.hutton.ac.uk/).

The indicators chosen in any basket also need to be deployed cost-effectively and preferably at a large scale. It may be that consideration is given to a set of indicators that can be deployed in such a manner, and another set of indicators that are investigated at a smaller number of sites and/or habitats where confirmatory evidence is required and/or there are good reasons to use these more expensive indicators. It should also be borne in mind that future advancements may help deploy indicators at a broader scale than is currently possible – testing such novel techniques could be another aspect of Phase 2 work.

6.4. Indicator Presentation

When choosing the basket of indicators, it may also be important to bear in mind how these are communicated and presented. For instance, it may be important to understand which indicators should be used at different ‘stages’ of ecosystem recovery. Although it is not the role of this report to establish which targets or goals represent recovery, it may also be useful to present where indicators and their values lie on any ‘road to recovery’, similar to the recovery wheel used in the International Principles and Standards of Ecological Restoration (Gann *et al.* 2019) (Figure 4).

(a)

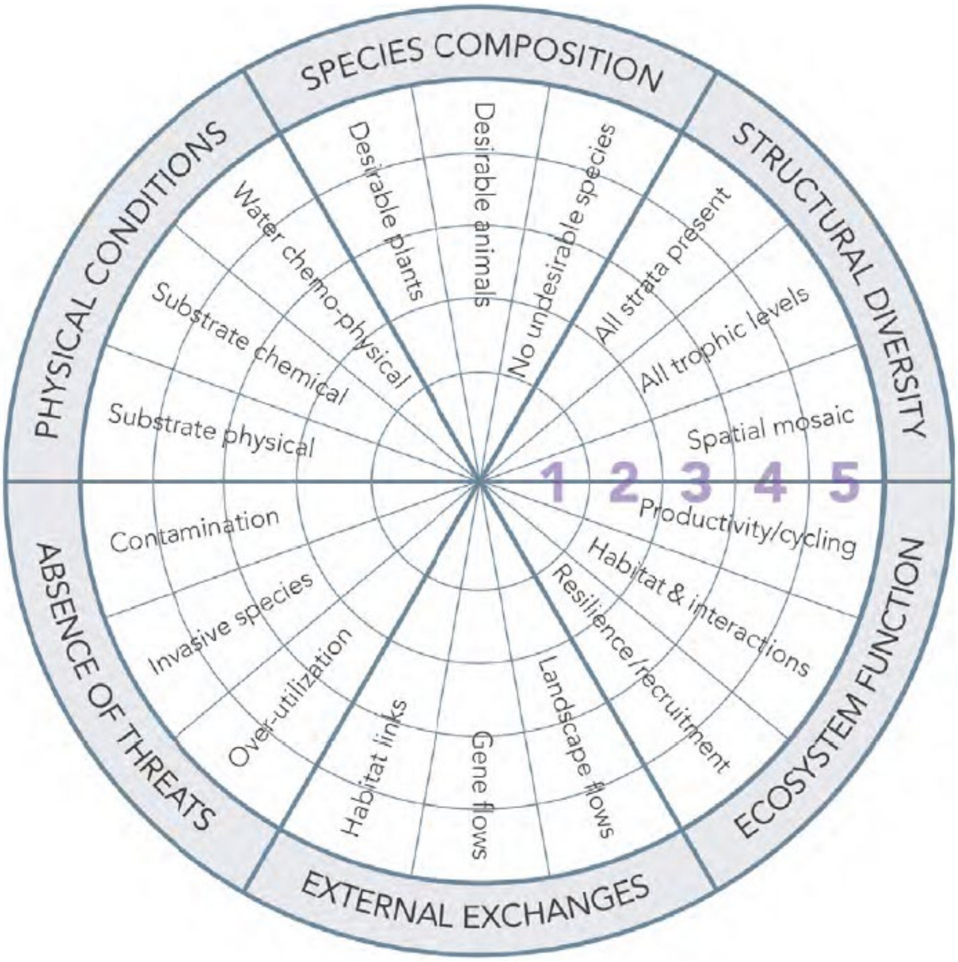
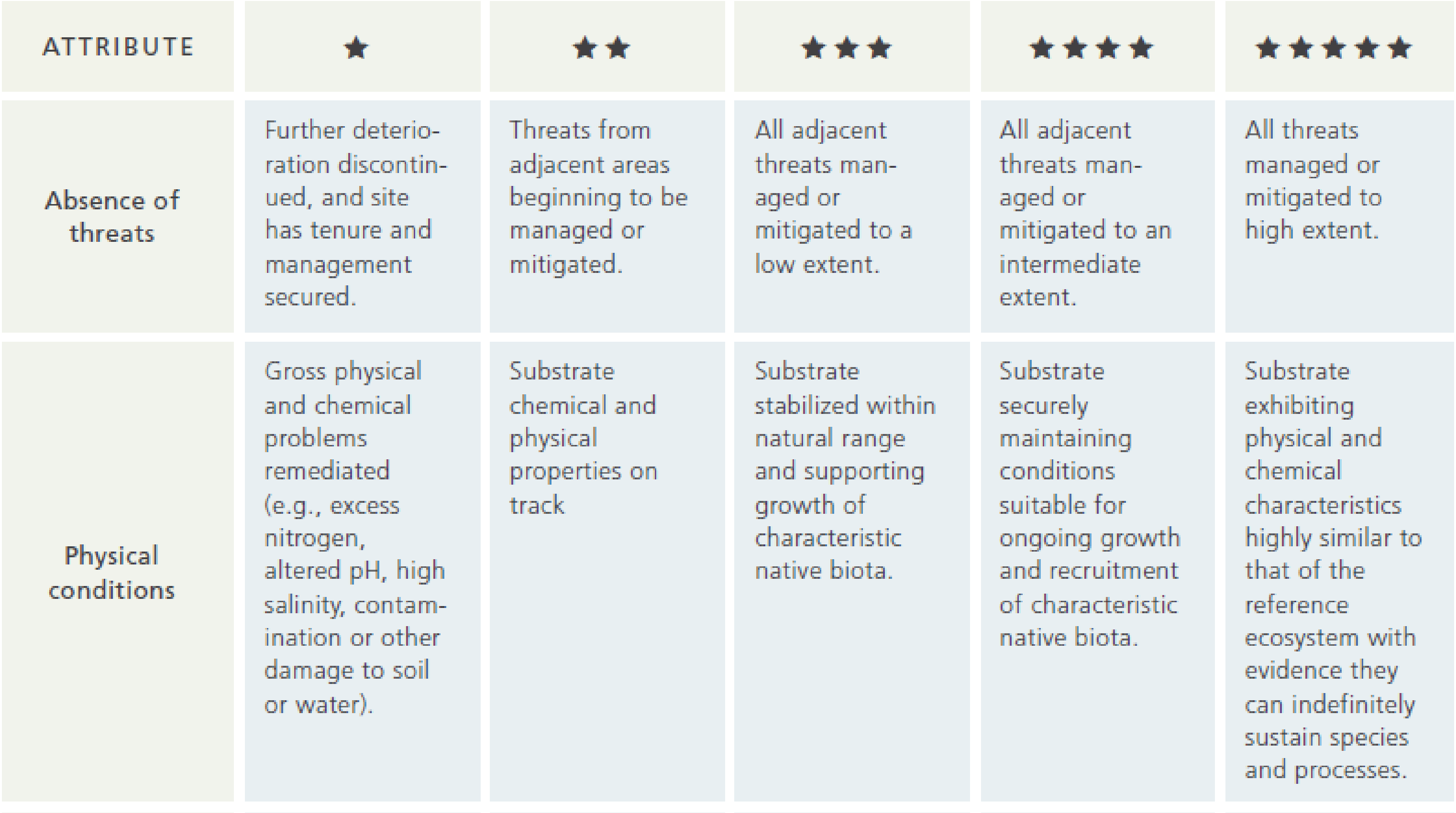


Figure 4a. The recovery wheel recommended by the Society for Ecological Restoration International. See Figure 4b for more information.

(b)



ATTRIBUTE	★	★★	★★★	★★★★	★★★★★
Absence of threats	Further deterioration discontinued, and site has tenure and management secured.	Threats from adjacent areas beginning to be managed or mitigated.	All adjacent threats managed or mitigated to a low extent.	All adjacent threats managed or mitigated to an intermediate extent.	All threats managed or mitigated to high extent.
Physical conditions	Gross physical and chemical problems remediated (e.g., excess nitrogen, altered pH, high salinity, contamination or other damage to soil or water).	Substrate chemical and physical properties on track	Substrate stabilized within natural range and supporting growth of characteristic native biota.	Substrate securely maintaining conditions suitable for ongoing growth and recruitment of characteristic native biota.	Substrate exhibiting physical and chemical characteristics highly similar to that of the reference ecosystem with evidence they can indefinitely sustain species and processes.

Figure 4: Conceptualisations of indicating recovery. (a) The recovery wheel recommended by the Society for Ecological Restoration International. This recovery wheel is meant to be an aid to understanding how recovered a given site is; for each element of the wheel there is (b) an accompanying table that shows what levels of any given indicator would need to reach to indicate 1* to 5* recovery. Consideration could be given to how to apply a similar scheme to any basket of indicators, and what would indicate different levels of recovery from atmospheric pollution in particular terrestrial habitats and/or ecosystems as an aid to policy makers. For restoration, clear goals are a requirement. This may be less of an issue for air pollution recovery indicators but a conclusion from the Principles and Standards may be pertinent: ‘Rather than assuming that the system will always follow a single [recovery] trajectory, it may be useful to develop a set of reference models for multiple potential trajectories.’

Table 2: Potential recovery indicators, including those that have been trialled previously and been shown to perform poorly as a measure of N impact. This list is a compilation of workshop discussion, and inspection of literature, in particular the NINE report (Britton, Fielding, and Pakeman 2023) and a section on indicators (Caporn *et al.* 2011) within the Terrestrial Umbrella (TU) report (Emmett *et al.* 2011) together with a RoTAP indicators table supplied by Chris Field. Indicative values (High, Medium, or Low) are shown for: Speed of response; Direction of response (↑ = increasing with recovery; ↓ = decreasing with recovery; ↔ = increase or decrease possible; ? = uncertain due to insufficient evidence); Specificity to N; and Cost. For' Speed of response', letters followed by a superscript 1 were taken from Britton *et al.* (2023). It is important to note that this list is preliminary, not exhaustive, and that the H/M/L scores given are only indicative. We recommend further work to populate a modified live version of this table, including columns to assess whether specific recovery indicators have only been used (or can only be used) in certain habitats. To establish whether historical data can be used to inform where recovery is coming from, it will also be useful to establish, within or across habitats, whether candidate indicators have been collected previously. It will also be important to calculate some measure of cost effectiveness (rather than just cost alone) and establish whether this can vary by the method adopted to assay the indicator. Columns could potentially be added for all criteria mentioned in Criteria for Selecting Indicator, Habitat and Species Priorities.

a) Indicators of pollution pressure

Indicator	Speed and direction of recovery response	Specificity to N	Cost	Remarks including whether previous poor performance was observed
Atmospheric NH_3 concentration	H ↓	H	L (passive) H (active)	Passive (e.g. 'Alpha') samplers are relatively cheap and indicate monthly mean concentrations. Active samplers are more expensive but give greater time-resolution and characterisation of peak concentrations.
Atmospheric NO_x concentration	H ↓	H	L (passive) H (active)	Passive (e.g. 'Gradko') samplers can be used. Active samplers are more expensive but give greater time-resolution and characterisation of peak concentrations.
Nitrogen deposition (wet, occult, and dry)	H to M ↓	H	M (bulk) H (DWOC)	Bulk collector and fortnightly analyses. Daily-wet only collectors (DWOC) – more expensive but gives greater time-resolution and minimises the effects of dry deposition into samples
Nitrogen deposition (cloud/fog/mist)	H to M ↓	H	H	Fog collectors, samples collected typically fortnightly

b) Indicators of biogeochemical response

Indicator	Speed and direction of recovery response	Specificity to N	Cost	Remarks including whether previous poor performance was observed
Vegetation productivity	M ↓	L	H	Indicative of eutrophication, but influenced by other factors, so unsuitable for a single site condition assessment.
Biomass	M ↓	L	L–H	Strongly influenced by other factors – not suitable for single site condition assessment. Best measured in exclosures to reduce effects of grazing, although small herbivores (e.g. invertebrates) are always present.
Tree or shrub growth increment	M ↓	L	M	*Calluna* ring measures were successfully applied to look for historic differences in growth (Lageard *et al.* 2005; Kowal *et al.* 2024).
Vegetation height (ground measurement or LIDAR)	M ↓	L	L	Strongly influenced by other factors – not suitable for single site condition assessment.
Vegetation greenness e.g. Normalised difference vegetation index DVI	M ↓	L	L	Strongly influenced by other factors – not suitable for single site condition assessment.

Indicator	Speed and direction of recovery response	Specificity to N	Cost	Remarks including whether previous poor performance was observed
Tissue N in mosses	M[1] ↓	M	L	Suggested as a broad scale cross-habitat indicator (Britton, Fielding & Pakeman 2023); adjusting for the typical N content of each species was suggested by Rowe *et al.* (2017). Works well with *Racomitrium lanuginosum* in alpine/upland habitats (Armitage *et al.* 2012). However, Stevens *et al.* (2011) found that tissue N of *Rhytidiadelphus squarrosus* was not a good indicator of N deposition in acid grasslands across Europe, and the Terrestrial Umbrella (TU) report (Emmett *et al.* 2011) found that moss N was only increased by N addition in dune grassland, and stated 'moss tissue N has been used successfully in previous surveys…in this study it showed a limited response, perhaps due to a long survey period and N-stimulated growth dilution'.
Tissue N/P in mosses	H ↓	L	M	Increased with N addition in dune grassland, some evidence of increase in acid grasslands and bogs (Emmett *et al.* 2011). However, saturates at deposition values less than 10 kg N ha^{-1} yr^{-1} in *Racomitrium lanuginosum* in alpine habitats so potentially limited suitability in UK context (Armitage *et al.* 2012).
Tissue N/P in plants	M ↔	L	M	Mentioned in RoTAP report as one of the '**core indicators**'. However, in a 1998–99 survey *Calluna spp.* N/P was found to decrease with more N deposition, presumably due to increased P acquisition (Rowe *et al.* 2008).
Soluble ammonium in plant tissue	H ↓	H	M	Mentioned in RoTAP report as one of the better '**core indicators**'. But moderately complex assay possibly influenced by season.

Indicator	**Speed and direction of recovery response**	**Specificity to N**	**Cost**	**Remarks including whether previous poor performance was observed**
Tissue N in lichens	M[1] ↓	H	L	Tissue N reacts quickly due to many lichens being oligotrophs and potentially useful for mapping N activity and N deposition to lichens (Boltersdorf & Werner 2014)
Tissue N in vascular plants	L[1] ↓	H	L	In a 2009 survey, *Calluna* spp. tissue N increased with increasing N deposition but only in upland heaths, while in experiments responses were seen at lowland heaths and bogs (Emmett *et al.* 2011) (see also Sheppard *et al.* 2008; Jones *et al.* 2008). Also noted by Edmondson *et al.* 2010 and Caporn *et al.* 2014 for heathland. Britton et al (2023) note that Stevens *et al.* 2011 tested tissue N of *Agrostis capillaris* and *Galium saxatile* across acid grasslands in Europe as indicators of deposition but none performed well. Whole-community tissue N could be considered (e.g. Community Weighted Mean) which accounts for intraspecific variation as well as compositional change.

Indicator	Speed and direction of recovery response	Specificity to N	Cost	Remarks including whether previous poor performance was observed
Tissue N through FTIR	L ↓	L	L	The Fourier-Transformed InfraRed (FTIR) spectrum of plants or of vegetation is related to N content, among other factors. Gidman *et al.* (2006) found that FTIR spectra of *Galium saxatile* could be related to nitrogen deposition, but the predictive power of the relationship was weak, and they concluded that the method needed further development. Kalaitzidis *et al.* (2008) reached similar conclusions for *Calluna vulgaris*. More recent studies have shown that spectra can detect differences between species, but that they are also strongly affected by plant canopy morphology and other factors (Girard *et al.* 2020; Moeneclaey *et al.* 2022). Monocultures are one thing; complex semi natural communities are another. Girard *et al.* suggest that in context of detecting N impacts the technique is best suited to remote sensing of biodiversity changes rather than detecting within-species change.
Litter N (total)	M ↓	H	L	Litter N content indicates N translocation before senescence, so may better reflect plant N limitation than live-tissue N.
Litter N (KCl-extractable)	M ↓	H	M	Increased with increasing N deposition in TU survey but only in upland heathland habitat. Increased very sharply above a threshold of 17 kg N ha^{-1} yr^{-1}. Experiments showed increases in bogs and lowland heath too.
Soil pH	M[1] ↑	L	L	Responded across all habitats (acid grasslands, bogs, lowland heaths, upland heaths) except sand dunes (Emmett *et al.* 2011; Field *et al.* 2014). RoTAP mentions can respond to several factors.

Indicator	Speed and direction of recovery response	Specificity to N	Cost	Remarks including whether previous poor performance was observed
Soil %N or N stock	L[1] ↓	M	L	Unresponsive in TU 2011 report but previously shown to be sensitive at experimental sites (Emmett *et al.* 2011)
Soil C/N	L ↔	M	L	Unresponsive in TU 2011 report but previously shown to be sensitive at experimental sites (Emmett *et al.* 2011). RoTAP suggests not always related to N deposition. Can be useful where thresholds are known in relation to leaching in certain habitats (Rowe *et al.* 2006).
Microbial C/N	M ↑	M	H	In RoTAP report
Soil soluble N	M[1] ↓	H	M	Commonly measured in a KCl extraction as NO_3^- plus NH_4^+, although dissolved organic N could be included. Alternatively, may be measured using ion-exchange resins such as Plant Root Simulator (PRS) probes (https://www.westernag.ca/innov), which provides a time-integrated measure of N in the soil solution. Soluble N may not accurately reflect N availability in low-N systems where plant uptake and/or immobilisation remove N rapidly from solution.
Leaching of NH_4^+ and NO_3^-	M[1] ↓	H	H	Measured in samples from tray or suction lysimeters. Similar considerations to extractable soluble N (see above). At Budworth there was N leaching even at the background N deposition rate because of topsoil stripping (Field *et al.* 2013). For forests, see Dise and Wright (1995).
Soil base cation saturation (% of cation exchange capacity)	M ↑	L	H	More reliable indicator of acidification and recovery than soil pH (RoTAP). Be aware of management changes if comparing with old sites.
Soil base cation / Al^{3+} ratio	M ↑	L	H	In RoTAP report.

Indicator	Speed and direction of recovery response	Specificity to N	Cost	Remarks including whether previous poor performance was observed
Mineralisable N	M ↓	H	H	A ‘**core indicator**’ (RoTAP). Potentially a better indicator of N status than soil soluble N and shown to be a good predictor of mean Ellenberg N (an indicator of eutrophication, see below) by Rowe *et al.* (2011).
Nitrification	M ↓	M	M	In RoTAP report. Nitrate proportion of mineral N was found to increase with N deposition, particularly in mineral soils (Rowe *et al.* 2012).
Denitrification (N_2O emissions)	M ↓	H	H	In RoTAP report.
Ecosystem respiration	M ↓	L	M	In RoTAP report. Indicated as ‘**core indicator**’ but not one of the best.
Metabolic quotient (respiration to microbial C)	M ↓	L	H	In RoTAP report. Indicated as ‘**core indicator**’ but not one of the best.
Biological N fixation rate	H ↑	H	H	Highly responsive to increased N availability (Zheng *et al.* 2019), but measurement is not straightforward. N budgeting is impractical for semi-natural systems; acetylene reduction is only a proxy measure; and ^{15}N natural abundance methods are approximate (see below).
Foliar $^{15}N/^{14}N$ ratio	Being investigated in Phase 1	L	M	Potential indication of mycorrhizal activity: higher ^{15}N values indicate plant’s reliance on inorganic N (i.e., from wet or dry deposition). Low values expected in mycorrhizal plants in clean habitats (Schulze, Chapin & Gebauer 1994; Vesala *et al.* 2021). However, also affected by the ^{15}N content of N inputs to the ecosystem (e.g. biological N fixation, deposited N) and of loss fluxes (e.g. denitrification).

Indicator	**Speed and direction of recovery response**	**Specificity to N**	**Cost**	**Remarks including whether previous poor performance was observed**
Moss phosphomonoesterase (PME) activity	H ↓	M	M	Increased across all habitats considered in TU report although only significant in bogs and upland heaths (Emmett *et al.* 2011; Southon *et al.* 2013). Note that since cessation of treatments in UKREATE, this has decreased at Budworth (Chris Field, pers. comm).
Moss chlorophyll fluorescence (FvFm)	H ↓	L	L	In TU report, habitats showed different responses – significant increase with N in sand dunes, tendency to increase in bogs, tendency to decrease in lowland and upland heaths.
Lichen chlorophyll fluorescence (FvFm)	H ↓	L	L	Sheppard (2004) showed decrease in Fv:Fm in Cladonia with increasing N
Vascular plant chlorophyll fluorescence	M ↓	L	L	Mentioned in RoTAP report.
Other enzymes e.g. nitrate reductase activity, phosphatase	M ↓	M	M	Mentioned in RoTAP report as potential '**core indicator**'. However, insufficient field testing was noted, and they were not indicated as 'best' – at least for vegetation. They were indicated as one of better indicators in soil. In *Sphagnum* spp., NRA was reduced when ammonium was added (Press and Lee 1982).
Litter phenol oxidase activity	M ↓	L	M	Increased in *Calluna vulgaris* with increasing N deposition but only in upland heathland habitat. Experiments showed increase in bogs and lowland heath too.

c) Indicators of biotic response

Indicator	Speed and direction of recovery response	Specificity to N	Cost	Remarks including whether previous poor performance was observed
Plant species richness	L[1] ↔	L	M	Across habitats considered in the TU, plant species richness (including mosses but not liverworts) declined with N deposition. This decline was non-linear, with a rapid decline at low levels of N pollution (Field *et al.* 2014). Strongly related to N deposition in heathland (Edmondson *et al.* 2010; Caporn *et al.* 2014). Strongly related to N deposition in acid grassland, as was forb richness (Stevens *et al.* 2009). RoTAP indicated this as one of the best '**core indicators**' when referring to diversity generally. However, species richness can increase due to invasion of atypical species such as ruderals; it may therefore be important to consider beta-diversity as well as alpha-diversity (Kortz & Magurran 2019). Detailed experimental work at Whim Bog (Sheppard *et al.* 2011; Levy *et al.* 2019) has shown plant species decline in peatlands with clear shift towards *Eriophorum*-dominated habitats.
Graminoid / forb cover ratio, or forb / total cover ratio.	L[1] Graminoid / Forb ↓ Forb / Total ↑	M	M	Best indicator of N pollution of those tested for acid grassland (Stevens *et al.* 2009). A better indicator than species-specific indicators in acid grasslands across Europe, as was forb richness alone (Stevens *et al.* 2011). The 'forb / total cover' ratio is more mathematically stable (Rowe *et al.* 2016). Also, in RoTAP report.

Indicator	Speed and direction of recovery response	Specificity to N	Cost	Remarks including whether previous poor performance was observed
Mean 'Ellenberg N' score	L ↓	M	M	Ellenberg N indicates nutrient (not only nitrogen) status and is considered a proxy for the fertility or vegetation productivity of the site. In RoTAP report as '**core indicator**' but not one of the better ones. Change in mean Ellenberg N over time at a given site could be useful to indicate changing N deposition pressures providing nothing else is influencing the fertility of the soil at the site.
Mean 'Ellenberg R' score	L ↑	L	M	Mean Ellenberg R is a reasonably accurate indicator of soil pH and hence of acidification and recovery.
Plant CSR signature	L Towards Stress-tolerance	L	M	Plant species can be characterised on the three axes of Competitiveness, Stress-tolerance and Ruderality, and the mean scores provide an indication of assemblage-level responses. Mentioned in the RoTAP report.
Lichen abundance (terrestrial)	L-M ↑	M	L	Used in Kowal *et al.* (2024) to measure recovery in lowland heath. Also looked at lichen community diversity.
Lichen abundance (epiphytic)	M-H ↑	M	L	Assemblages of lichens that have preference (or not) for N correlate well with N exposure in the field and are more reliable than single species indicators. As stated by RoTAP and noted as one of the best '**core indicators**'. Note that species present can be influenced by bark chemistry.
Lichen species richness	M ↑	M	H	Proposed as a sensitive indicator of nitrogen in ground dwelling and epiphytic communities in woodland canopies – see Rogers, Moore & Ryel 2009; Stevens, Smart *et al.* 2012, as cited in Britton *et al.* (2023).

Indicator	**Speed and direction of recovery response**	**Specificity to N**	**Cost**	**Remarks including whether previous poor performance was observed**
Lichen trait and taxonomy	M Direction depends on the specific trait	M	L	Lichen functional traits can be used to infer levels of excess nitrogen through the observed impact on lichen epiphyte communities (Delves *et al.* 2023). Methodology developed to assist in locations where knowledge is limited.
Lichen/bryophyte health	H ↑	M	L	Strong impacts can be visually assessed with death, growth reductions, bleaching and algal invasion clearly observable in high N environments (Sheppard *et al.* 2011).
Bryophyte species richness	M ↑	M	H	Strongly related to N deposition in heathland (Edmondson *et al.* 2010; Caporn *et al.* 2014).

Indicator	Speed and direction of recovery response	Specificity to N	Cost	Remarks including whether previous poor performance was observed
Mycorrhizal assemblage	?	?	M-H	Being investigated in Phase 1. Studied in forests, individual taxa and sets of taxa. Community diversity analyses using molecular techniques are already being used across different habitats to assess mycorrhizal fungal types (van der Linde *et al.* 2018; Suz *et al.* 2021; Van Geel *et al.* 2020; Kowal *et al.* 2022; Kowal *et al.* 2024). Ongoing effects from N fertilization experiments 10+ years since treatment on Thursley Common, Surrey. High-throughput technologies could allow rapid and cost-effective assessment of root and soil biodiversity in the future, but they do not allow the assessment of active communities or assignment of host specificity. Visual identification allows checking for active communities and assessment of functional traits. Might need to be coupled with DNA methods. Examining ink-stained roots for endomycorrhizal colonisation and root tips for characterisation of ectomycorrhizal morphotypes (i.e. presence of rhizomorphs), is important to understand shifts in bi-directional nutritional function between host plant and mycorrhizal fungi.
Soil fauna assemblage	?	?	H	Potentially useful indicator, but little evidence of N impacts to date.
Butterfly Community Nitrogen Index	? ↓	?	M	Community Nitrogen Index for butterflies in Netherlands – uses data from Dutch national butterfly monitoring scheme and combines it with Ellenberg N values for plant community in which butterfly has highest occupancy to give metric of average N preference of butterfly community at site (Wallis DeVries & van Swaay 2017).

Indicator	**Speed and direction of recovery response**	**Specificity to N**	**Cost**	**Remarks including whether previous poor performance was observed**
Mycorrhizal colonisation	Being investigated in Phase 1.	?	M	Previously looked at across an atmospheric N deposition gradient specifically for arbuscular mycorrhiza *Mucoromycotina* and *Lycopodiella inundata* (Kowal *et al.* 2022) but no direct inputs at the site level.
Indicator species – whether vascular plant, bryophyte, lichen, mycorrhizae, or fauna	L-H Direction depends on the species	M-H	L	Individual species may be highly indicative of N pollution. Depending on which species is chosen, there may be prior records. Good to consider species that are more affected by competition vs those species that may be directly impacted by atmospheric concentrations. Species that occupy different canopy levels (depending on habitat).
Flowering, e.g. number of flowers per area	M ↑	L	L	-
Bioacoustics	? Direction depends on the species	?	M	Automated processing of sounds recorded using acoustic and hyper acoustic microphones allows identification of birds, bats, Orthoptera and other animals. The method has potential for studying the recovery of individual species and faunal assemblages.

7. Key Recovery Indicators

Ideally, we would arrive at a set of key indicators that can clearly demonstrate recovery from N pollution. As the foregoing sections have made clear, this is not a straightforward task since not all indicators may respond equally in all habitats, not all indicators that have been used to show impacts of increasing N may respond to declining N, and different indicators will have different scores, and thus strengths and weaknesses, across the breadth of criteria. Within the resource constraints of this report, it has not been possible to fill in the values for all criteria for all possible indicators, nor has it been possible to assess the data that already exist that may further help determine key recovery indicators. We recommend that these aspects are developed to help inform indicator choice. Finally, the indicators that are most appropriate to indicate recovery from N pollution may also depend on the policy and/or science question being posed at the time.

Therefore, we currently do not provide a shortlist of ‘key recovery indicators. We do recommend that a basket of indicators is considered, since it is highly unlikely any one indicator will score highly across all criteria that would lie behind decisions. Further, this basket needs to consider representation across indicator types (pressure, biogeochemical response, biotic response, derived indicators), including across a range of likely response times. A consideration of the whole ecosystem may be worthwhile. For instance, a vertically integrated approach that incorporates above- and below-ground indicators from across trophic levels and functional roles, to ascertain the degree of recovery, preferably against appropriate benchmarks, may benefit from an integration of previously used and novel indicators. If novel indicators can be collected more cost-efficiently than the previously used indicators but be demonstrated to be as effective at characterising declining N pressure, future work could then consider adopting the novel indicator more widely. The efficacy of these indicators would need testing, potentially using a range of study approaches as explained earlier. In addition, indicators need testing in different habitats (as they may not apply equally to all), with the adopted basket approach justifying indicator choice for any given habitat.

8. Existing Survey Networks

Table 3 provides a preliminary assessment of existing survey networks and data that could contribute to an understanding of recovery indicator responses to declining N deposition within the UK, providing the remarks are accounted for in a robust manner. We recommend making this a live table and inviting contributions from the wider air pollution community to consider whether other gradient sites offer potential, and to consider whether gradient extremes could be found in locations outside of the UK but in otherwise similar climatological and geomorphological contexts which could further contribute to understanding of recovery dynamics from N pollution.

Table 3. Existing survey networks and projects that could potentially contribute data to test which indicators can provide evidence of recovery from declining atmospheric N pollution.

Existing Networks / Project	What indicators (broad categories)	Remarks
Countryside Survey (CS)	Soil properties Vegetation	Permission required for use outside of original collection. Need to understand which CS squares have declining N deposition pressures and which don't – this level of granularity is not feasible at present. Furthermore, CS locations cannot be disclosed, so published results need to be spatially blurred such that the original locations are not identifiable.
National Plant Monitoring Scheme	Vegetation	Quadrats mainly revisited every year, although this varies due to uptake by citizen scientist recorders. At some sites vegetation lists are recorded as full inventories, but at others less experienced recorders can sample using pre-defined species lists
tNCEA (Terrestrial Natural Capital Ecosystem Assessment)	Soil health (broad sense) Soil and root fungi (Kew); soil fauna; soil chemistry (carbon storage)	Kew implementing mycorrhizal research into their monitoring efforts across England to set up baseline. UK-wide samples from 100s of monads/year from grasslands to forests. Hopes to repeat on a five-yearly cycle. The programme will produce updated national habitat maps and England peat maps. This can be layered with fine scale N-deposition maps.
Racomitrium heath gradient study	Vegetation Soil chemistry Soil biology	36 sites across the UK and Europe, including low deposition comparator sites in Iceland, Norway, and Faroes. Initial vegetation and soil data collection 2006/07 with additional aspects of ecosystem responses (e.g. soil biology) investigated in subsequent years.

Existing Networks / Project	**What indicators (broad categories)**	**Remarks**
Environmental Change Network (ECN)	Vegetation Soil chemistry Stream chemistry Fauna–butterflies Fauna–moths Air quality–NO_2	11 long-term monitoring sites across the UK
UKEAP (UK Eutrophying and Acidifying Pollutants) Network for N	Atmospheric concentrations of NH_3 and (at some sites) NH_4^+	NH_3 is monitored monthly at approx. 72 sites across the UK.
Natural England's Long Term Monitoring Network	Vegetation Soil chemistry Soil fauna Fauna–butterflies Air quality	37 long-term monitoring sites across England sampled since 2009. Co-located air quality, weather, vegetation, and butterfly community data is available at some sites. Vegetation sampling methods are directly comparable to ECN.
UK Butterfly Monitoring Scheme	Fauna–butterflies	2,000+ sites monitored across the UK since 1976.
Rothamsted Insect Survey	Fauna–moths	Moth light traps are run at around 80 locations across the UK and Ireland. Data are available from the past 50 years.
National Moth Recording Scheme	Fauna–moths	Over 34 million current and historical records of moths across the UK.
Shared Nitrogen Action Plan pilots (England) SNAPDRAGONS (Wales)	Air quality monitoring Vegetation surveys	Five SNAP pilots in England.
Catchment Sensitive Farming	Air quality monitoring Vegetation surveys Landscape scale effects	EA-funded pilot project Air Quality Monitoring and Modelling (AQMM) in N Cumbria (Wedholme Flow)
Protected Sites Strategy	Air quality monitoring Vegetation surveys	NE-funded pilot project (CANS: Cumbria Atmospheric Nitrogen Strategy) at three SSSIs in S Cumbria

9. Existing Experiments

The UKREATE consortium (Eutrophication and Acidification of Terrestrial Ecosystems in the UK) experiments provide an invaluable opportunity to understand indicator recovery trajectories from N addition at the plot scale. They also provide an ideal opportunity to test whether suggested indicators do, indeed, work as indicators of recovery from air pollution, specifically N deposition.

The UKREATE consortium brought together a series of experiments across semi-natural habitats in the UK (Figure 5), with different timescales and amounts of N addition (Table 4). Most sites have ceased to add N, so they now provide a series of control and treated plots where trajectories of recovery can be compared. Other sites continue to add N, but consideration could be given to ceasing addition in some plots (if replication permits) to understand recovery in those plots (or plots could be split, as occurred in e.g. Ruabon). Furthermore, a plethora of data exist from the impact phase of these experiments, with potential to understand dynamics during and after N deposition. These sites also offer the opportunity to trial novel indicators. This opportunity only exists where relationships with historically available proxies can be developed.

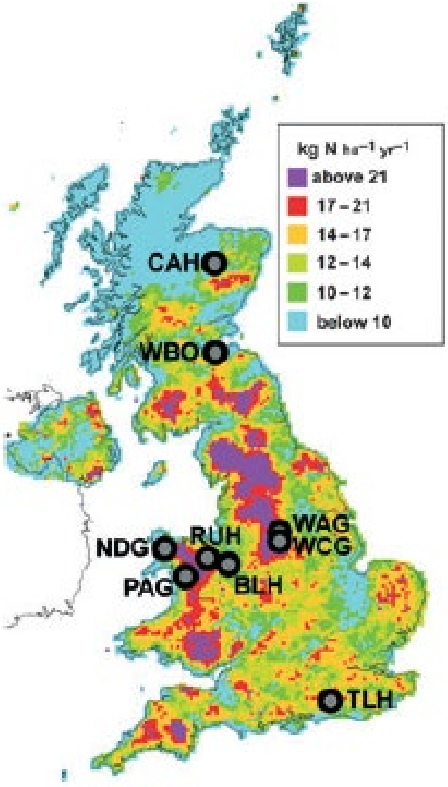


Figure 5. UKREATE site locations – reproduced from Figure 1, Phoenix *et al.* (2012). Map shows total N deposition modelled for 2008 (RoTAP 2012). CAH = Culardoch; WBO = Whim Bog; WAG = Wardlow – acid grassland; WCG = Wardlow – calcareous grassland; RUH = Ruabon; NDG = Newborough; PAG = Pwllpeiran; BLH = Budworth; TLH = Thursley. As shown in Table 4, some of these sites have multiple experiments.

As noted in Table 4, additional N addition experiments from across the UK could also be used to explore indicator recovery trajectories, with the potential to consider international experiments with similar climatological and geomorphological conditions. Additional columns in Table 4 (e.g. based on environmental context) can be used to identify key habitats and locations where (experimental) knowledge of atmospheric N pollution is lacking – for instance, south west England, the Breckland, and the temperate deciduous ‘rainforests’ of north west Scotland (noting gradient studies e.g. Mitchell *et al.* 2005; Ellis & Coppins 2010). Depending on habitat prioritisation, this could indicate areas where Phase 2 empirical work could be expedited. As emphasised in our Recommendations, we suggest this and other Tables be amended (e.g. additional columns where relevant) and made ‘living’ documents where access is given to the air pollution community to add their knowledge of available data sources.

Some of the UKREATE experiments considered modifying factors (see Remarks column in Table 4). Future experiments could also consider how restoration/management interventions (e.g. topsoil stripping, grazing) or other factors (e.g. climate) modify recovery trajectories. It may be that in some instances additional management is required to kick-start recovery since hysteresis would otherwise prevent recovery, even with declining N deposition. Identifying under what conditions hysteresis is expected to be important in hindering recovery is an open science question.

Phase 2 could consider the need to extend simple distributed experiments to not only include recovery from atmospheric N but also restoration actions and/or climatological changes. Such experiments could also help ascertain specificity of the indicator to declining N in relation to simultaneous environmental changes. Britton *et al.* (2023) highlight that most management studies they found related to the southern UK or were from Europe. Those studies did suggest that some management activities can mitigate nitrogen impacts: liming was able to reduce acidification in grasslands and forests and grazing or mowing improved sward structure and helped to maintain species richness in grasslands (Stevens *et al.* 2013). Management options were best explored in heathlands with burning, grazing, mowing, and turf cutting all showing potential to reduce nitrogen stocks. However, Britton *et al.* (2023) cautioned that management interventions can have undesirable negative side-effects e.g. increased nitrogen leaching following soil/vegetation disturbance, loss of carbon stocks, and/or reduction in habitat suitability for fauna (see also Jones *et al.* 2017a, 2017b; Maes *et al.* 2017). For heathlands, the conclusion was that there was a risk that trying to solve one problem (i.e. nitrogen pollution) could create another (Britton, Fielding & Pakeman 2023).

Table 4: Summary of existing N deposition experiments across the UK, both within and outside of the UKREATE network (see Phoenix *et al.* 2012 for further details e.g. soil type, NVC communities and application method). These experiments could provide a basis for understanding indicator recovery trajectories while gap analyses can highlight where additional work may be needed, including by habitat, soil type or N form. Such analyses could also extend to understanding availability of international experimental sites in similar bioclimatic and geomorphological contexts where insight into indicator recovery trajectories could be gained. We recommend this table is made into a living spreadsheet, where additional columns are added to indicate climate, geomorphology and any available recovery data from the different sites. The former contextual variables will aid gap analyses; the latter will inform indicator identification and prioritisation. Key N impact findings (including in relation to background N pollution) could also be summarised in this (or another) table to help understand where recovery is 'starting' from in these different sites, including from published sources.

UKREATE sites

Site name	Habitat(s)	Experimental treatments and levels (solution application unless otherwise noted: kg N ha^{-1} yr^{-1})	N addition (start and end year)	Remarks
Whim Bog	Bog	0, 8, 24, 56 wet deposition of NH_4Cl and $NaNO_3$. 4–70 as NH_3 gas in transect.	2002 – ongoing	Dosing of ammonium (NH_4^+) and nitrate (NO_3^-) coupled with rainfall to simulate read world conditions. Ammonia (NH_3) concentrations released to match a small emission source with monthly concentrations from 80 µg m^{-3} to below the critical level.
Ruabon (Upland)	Heath	0, 40, 80, 120 as NH_4NO_3	1989 – 2020	-
Ruabon (Upland)	Heath	0, 10, 20, 40, 120 as NH_4NO_3	1998 – 2002 / 2020	In 2002, plots split in half to allow recovery to be observed. Since 2020, experimental N addition ceased to all plots.
Budworth (Lowland)	Heath	0, 20, 60, 120 as NH_4NO_3	1996 – 2020	-
Thursley (Lowland)	Heath	0, 7.7, 15.4 as $(NH_4)_2SO_4$	1989 – 1996	-
Thursley (Lowland)	Heath	0, 30 as $(NH_4)_2SO_4$	1998 – 2010	In 2021, plots were evaluated by Kowal *et al.* 2023 (in review). There were significant lingering vegetation structural, lichen community and bryophyte, soil chemistry (e.g. pH) and soil fungal community differences. New plots added 2023 to receive NH_4NO_3 treatments and NH_4NO_3 x fire with short-term recovery to then be followed.
Culardoch (Montane)	Heath	0, 10, 20, 50 as NH_4NO_3	2000 – 2011	Interaction with warming, burning, and clipping. Measurements/monitoring continued 2011–2022

Site name	Habitat(s)	Experimental treatments and levels (solution application unless otherwise noted: kg N ha^{-1} yr^{-1})	N addition (start and end year)	Remarks
Pwllpeiran (Acid)	Grassland	0, 10, 20 as $NaNO_3(NH_4)_2SO_4$	1996 – 2012	-
Wardlow (Acid)	Grassland	0, 35, 70, 140 as NH_4NO_3	1990 – 2002	-
Wardlow (Acid)	Grassland	0, 35, 140 as NH_4NO_3	1995 – ????	-
Wardlow (Calcareous)	Grassland	0, 35, 70, 140 as NH_4NO_3	1990 – 2002	-
Wardlow (Calcareous)	Grassland	0, 35, 140 as NH_4NO_3	1995 – ???	-
Newborough	Sand Dunes	0, 7.5, 15 as NH_4NO_3	2003 – 2011	Full interaction of N additions and grazing, with additional N+P treatment; N applications stopped after 2011, grazing exclusion continued until present; soils last sampled in 2011, vegetation re-surveyed in 2021.

Other potential UK experimental sites

Site name	Habitat(s)	Experimental treatments and levels (solution application unless otherwise noted: kg N ha^{-1} yr^{-1})	N addition (start and end year)	Remarks
Glencorse	Birch woodland	Ammonia (NH_3) gas released, and responses measured along transect within woodland	2021 – ongoing	Created to assess impacts of NH_3 on epiphytic lichens and bryophytes and ground flora within a woodland canopy. NH_3 concentrations released match a small emission source, with monthly concentrations from 30 μg m^{-3} to below critical level. Note an additional site created in Sri Lanka in 2022 (Deshpande *et al.* 2024).
Thursley – APRI Phase 1 study	Heath	-	-	30 (4x4 m) plots will test direct N input and responses and recovery of mycorrhizal fungi communities, using novel soil and root fungal indicators.

Site name	Habitat(s)	Experimental treatments and levels (solution application unless otherwise noted: kg N ha^{-1} yr^{-1})	N addition (start and end year)	Remarks
Tadham Moor	Lowland meadow	0, 25, 50, 100, 200	1986 – 1994	Examining recovery after 15 years, Stevens *et al.* (2012) showed that historic levels of fertilizer addition had no significant legacy in plant tissue chemistry. However, KCl-extractable ammonium N, total soil N, total organic carbon and microbial biomass N differed between the controls and higher historic levels of N addition. The species composition of the vegetation showed effects of historic N addition: mean Ellenberg N values were significantly higher in the control than most treatments

10. Key Habitats

Prioritisation of understanding whether recovery indicators work in certain key habitats could be based on rarity of the habitat in the international or national context, or its responsiveness to changes in pressure from nitrogen. At the same time, a widespread habitat can be of importance to nature and people so understanding its recovery from air pollution could also be prioritised. If we expect significant change around critical levels or critical loads, habitats to be investigated could also be prioritised based on whether they lie close to current critical levels/loads in particular areas. Indeed, recovery could be monitored across a gradient of exceedances of critical levels/loads. Such a design would exploit the previously mentioned priority sites based on, for example, cessation of N addition whether through experimental treatments or closure of an emission source.

The Nitrogen Decision Framework (NDF) (Jones *et al.* 2016) also provides a rationale for determining habitats to prioritise. For instance, the Factor 1 table associated with the NDF suggests that alluvial woodland, some types of strandlines and shingle beaches, and lowland swamps, are not sensitive to N, so recovery trajectories would not be of interest. However, most semi-natural habitats are suggested to be sensitive to N deposition. These include habitats that have rarely been (experimentally) investigated for N impacts in a UK context, for instance habitats in south west England and the Breckland, habitats in northwest Scotland, saltmarshes, and rocky habitats (e.g. limestone pavements, and woodlands - especially coastal temperate rainforests). The NINE report (Britton, Fielding & Pakeman 2023) emphasizes that 40% of key habitats, in a Scottish context, are currently lacking evidence in relation to thresholds of nitrogen impact, including areas of biodiversity importance: rocky areas, alpine habitats, scrub, and wetlands. This suggests careful experiments or survey designs would be required to understand recovery pathways in many habitats where N impacts have not already been recorded. This may be especially pertinent if they are widespread or an important feature in the landscape.

11. Recommendations

11.1. Phase 2 Recommendations

- Develop a list of priority recovery indicators, with a summary of what expected recovery would look like (i.e. the direction of change), and over what timescales.
- Create a basket of indicators, that helps with understanding recovery processes across a range of priority habitats at a range of timescales. If this is not possible, create baskets appropriate to specific habitats.
- Consider having at least one indicator in any basket that appeals to the public. This may enable investment and harnessing of citizen-science approaches.
- Consider how to present and communicate recovery from air pollution pressure. This needs to include having sufficient benchmarking data to allow interpretation of results from single sites.
- Develop a living table, to be populated in future work, with indication of which indicators fit which criteria (e.g. specificity, sensitivity, applicability, bidirectionality), and other properties identified in Criteria for Selecting Indicator, Habitat and Species Priorities. This table could also indicate the prior data that are available to help understand recovery from N impacts across indicators across different sites.
- Develop a living table which highlights existing survey networks that could contribute data for testing of recovery indicators. JNCC and other organisations should keep a watching brief on opportunities presented by (re-)survey studies along environmental gradients, providing that change in N pressure can be robustly estimated.
- Develop a living table with information on experimental sites that could inform recovery from N deposition in Phase 2. This table should include contextual environmental information to enable analysis of gaps in habitat coverage / environmental space.
- Focus Phase 2 work on testing potential recovery indicators in systems where N pollution pressure is known to have declined. This could include UKREATE sites and other experiments where N addition has ceased (and background rates can be estimated), and/or point sources of N pollution that have ceased operation, preferably with the super-imposition of a controlled experiment to isolate effects of declining N input.

11.2. Science Recommendations

- Develop understanding of when hysteretic responses may be expected, and over what timescales. This will inform expectations as to the degree of recovery possible, in what properties, and when.
- Investigate how different management interventions, across a range of habitats and environmental contexts, influence recovery trajectories from N pollution.
- Test prioritised recovery indicators across habitats and environmental contexts.
- Investigate under-researched habitats and locations, especially from an experimental perspective, such as rocky habitats and temperate rainforest, and southwest England and Breckland. This will help elucidate both N impacts and N recovery trajectories.
- Horizon scanning of future threats, potentially informed by Nitrogen Futures approaches (Dragosits *et al.* 2020): including risks from habitat alkalisation, future fuels, and changes in atmospheric composition. This should include improvement in modelling of future N deposition scenarios through greater understanding of how changes in atmospheric chemistry (including non-nitrogen compounds) will influence concentrations and deposition of N.

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Appendix 1: Workshop Participants

* = Hybrid participation; ** = Opportunity to comment on report, not present at workshop.

Name	Organisation
Aamer Raza**	Environment Agency (EA)
Áine O'Reilly*	Department of Agriculture, Environment and Rural Affairs (DAERA), Northern Ireland
Andrea Britton*	The James Hutton Institute (JHI)
Carly Stevens*	Lancaster University
Carolyn Simpson*	Natural England
Chris Field	Manchester Metropolitan University
Dave Stone*	Joint Nature Conservation Committee (JNCC)
David Vowles	Department for Environment, Food and Rural Affairs (Defra)
Ed Rowe	UK Centre for Ecology and Hydrology (UKCEH)
Elena Arrigoni	Royal Botanic Gardens Kew (RBG Kew)
Felicity Hayes*	UKCEH (Chair of ICP Vegetation)
Frank Gilliam**	University of West Florida, USA
Hannah Risser	UKCEH
Jack Wilkinson	JNCC
Jeff Duckett	Natural History Museum (NHM), Queen Mary University London (QMUL)
Jenny Hawley*	Plantlife
Jill Kowal	RBG Kew
Katie Suding**	University of Colorado Boulder, USA
Kayla Wilkins	Trent University, Canada
Laura M. Suz	RBG Kew
Laurence Jones*	UKCEH
Lorna Marcham	University College Dublin, Ireland
Martin Bidartondo	Imperial College London, RBG Kew

Name	**Organisation**
Matthew Jones	UKCEH
Maude Grenier	UKCEH
Mike Perring	UKCEH
Rachael Howlett	JNCC
Robin Pakeman*	JHI
Silvia Pressel	Natural History Museum (NHM)
Susan Zappala	JNCC
Wieger Wamelink	Wageningen University Research (WUR), Netherlands
Zoe Russell**	Natural England

Appendix 2: Workshop Abstracts

7 – 8 November 2023, Kew Gardens and online

Abstracts

Ericoid mycorrhizal fungi as air pollution recovery indicators

Presenters: Laura Martinez-suz (Kew RBG), Silvia Pressel (National History Museum, London), Jill Kowal (Kew RBG), Elena Arrigoni (Kew RBG); Contributors: Martin Bidartondo (Imperial College London) and Jeff Duckett (National History Museum, London).

The research team will present the context, experimental design, and objectives for investigating mycorrhizal fungi as air pollution recovery indicators (Phase 1 of the APRI Project). Roots of dominant heathland plants in the Ericaceae family such as the common heather (*Calluna vulgaris*) form symbiotic associations with ericoid mycorrhizal fungi (ErM). These mycorrhizal fungi play a crucial role in enhancing their hosts' nitrogen and phosphorous uptake, especially in nutrient-poor soils, therefore playing a fundamental role in nutrient cycling. The project starts with co-located ammonia passive monitoring and ecological monitoring in *Calluna*-dominated dry heath at Thursley Common Nature Reserve that is part of the UK's Long Term Monitoring Network. This is a manipulation experiment that investigates effects of controlled burn alongside nitrogen additions and their relationship to ErM colonisation, root and soil fungal community composition and key soil chemical characteristics to predict recovery.

Recovery from nitrogen deposition: Perspectives from restoration ecology

Mike Perring (UKCEH)

Here, I will present some current perspectives in restoration ecology on ecosystem and habitat recovery in an era of environmental change. It will cover the latest ideas from the Society for Ecological Restoration's International Principles and Standards, as well as reflect on whether hysteresis and other properties of complex systems need accounting for when considering recovery pathways from N deposition. The aim is to provoke thought and discussion, especially regarding what constitutes recovery in an era of multiple environmental stressors, as we achieve the workshop objectives: what is the indicator (or indicators) that help ascertain the extent of ecosystem, habitat, and species recovery from N deposition?

Metrics and indicators for recovery from N deposition in Scotland: the NINE project

Andrea Britton (JHI)

The NINE project is part of the Scottish Government Strategic Research Programme 2022-27 and is undertaking a variety of research activities to explore the impacts of N deposition on Scottish semi-natural ecosystems. I will give a brief outline of the project and describe how we are using long-term datasets and experiments, alongside new studies, to investigate the impacts of N deposition in the context of climate change and to develop metrics and indicators of impact and recovery.

Nitrogen and Epiphytic Bryophytes

Jeff Duckett (NHM and Queen Mary University London)

Epiphytic bryophytes provide a supremely good indicator of air quality. Between the Clean Air Acts of 1956 and 1968, and the end of the last century, almost all the epiphytes that had been exterminated by soot and sulphur dioxide pollution had returned to London. More surprisingly however, epiphyte diversity has also increased this century. This is attributed to NOX from vehicle emissions, but this has never been confirmed. An analysis of stable nitrogen and oxygen isotopes will provide the answer since these differ between fossil fuels and the general environment. We now need to compare the isotope composition of key epiphytic bryophyte species collected before the industrial revolution, from the mid twentieth century, from around 2000 and from the present time.

Ammonia exposure studies, impacts and recovery

Matt Jones (UKCEH)

This talk will provide a brief overview of ammonia field enhancement studies, the observed impacts from which have been used as key evidence to inform critical levels of NH_3 (and loads of N). This includes the Whim Bog field facility which has provided an overview of NH_3 impacts on peatland species and habitat. The talk will also showcase recent establishment of a temperate woodland NH_3 enhancement facility near Edinburgh and the first-ever tropical enhancement system installed in Sri Lanka. This work links to ongoing studies being carried out in Northern Ireland assessing habitat recovery, and the wider debate on when to convert Whim into a recovery experiment.

Recovery from nitrogen deposition: a North American perspective

Frank Gilliam (University of West Florida)

In the United States, the Clean Air Act (CCA) of 1970 has proven highly effective in decreasing emissions of atmospheric pollutants, initially of oxidized sulphur and later, with the CCA Amendments of 1990, of oxides of nitrogen (N). Empirical data indicate reductions by 50% of reactive N emissions from power plants and vehicles in the US and subsequent atmospheric deposition. I will summarize work on predicting changes in structure and function of North American forest ecosystems in response to decreased N deposition using a hysteretic model. This model predicts varying lag times in recovery of soil acidification and nutrient leaching, surface water N concentrations/export, plant diversity, soil microbial communities, and forest carbon and N cycling toward pre-N impact conditions. Some responses, such as N concentrations in stream flow, are already apparent in some regions, whereas others will be long-term and difficult to distinguish from concurrent environmental changes associated with N biogeochemistry, such as elevated CO_2, climate change, reductions in acidity, invasive species, and vegetation responses to disturbance.

Varied effects of atmospheric nitrogen deposition on GB butterflies

Hannah A. Risser, Ed C. Rowe (UK Centre for Ecology & Hydrology), Susan Zappala (Joint Nature Conservation Committee), Susan Jarvis (UK Centre for Ecology & Hydrology) and Carly Stevens (Lancaster University)

Atmospheric nitrogen deposition has been linked with an overall loss of plant species richness and homogenisation of semi-natural habitats both in GB and elsewhere. We expect that nitrogen-induced changes in plant communities will impact invertebrate species through the loss of reproductive habitat, food plants and suitable microclimatic conditions caused by the shifts in composition of plant communities. Butterflies are often used as indicator species due to their sensitivity to environmental change, our comprehensive understanding of their ecology, and the existence of long-term datasets on their abundance and distribution. We performed a spatio-temporal analysis on data from the UK Butterfly Monitoring Scheme using generalised additive models to understand the complex and often non-linear relationships between butterfly trends and their drivers. We demonstrate that butterflies vary in their relationships with nitrogen deposition and highlight both species-level and potential trait-level differences.

The UKREATE nitrogen-manipulation experimental platforms – what were they and what recovery data do we have?

Laurence Jones (UKCEH)

This talk will give an overview of the nine UKREATE sites and the timeline of their addition and recovery treatments. It will describe what collated data is available, with a focus on the existing data that can tell us about timescales and nature of recovery, and the potential for revisiting these sites to answer new questions.

Appendix 3: Workshop Background Document

Air Pollution Recovery Indicators: establishing an evidence base.

Background document for the APRI Kew Gardens workshop, November 2023.

Ed Rowe[1], Mike Perring[1], Susan Zappala[2] & Rachael Howlett[2]

[1] UK Centre for Ecology & Hydrology; [2] Joint Nature Conservation Committee.

This document aims to stimulate discussions at a workshop at Kew Gardens, 7–8 November 2023. If you have any queries or immediate thoughts after reading it, please contact Ed Rowe (ecro@ceh.ac.uk) and Mike Perring (mikper@ceh.ac.uk), so that we can incorporate them in the discussion.

The workshop is part of the Air Pollution Recovery Indicators project, which focuses on atmospheric nitrogen (N) pollution. The damaging effects of excess N load and of gaseous ammonia on ecosystems are clear, but the processes and timescale of recovery following a decrease in pollution pressure are less well understood. The APRI project aims to fill this knowledge gap by delivering new scientific research with potential for developing an indicator or set of indicators for ecosystem, habitat, and species recovery. In the first phase of the project, below-ground responses were studied at a dry heathland site where experimental additions of nitrogen (N) had been made between 1998 and 2011, revealing lingering effects on ericoid mycorrhizae (Arrigoni *et al.* 2023). Phase 2 will expand on this work, for example by studying other ecosystems, habitats, or species, and may include further empirical research.

Nitrogen pollution can have eutrophying, acidifying and/or toxic effects on species and habitats. In unpolluted land ecosystems in the UK, it is a lack of N that usually limits plant growth, although limitations of other nutrients such as phosphorus can be important. Excess N stimulates the growth of tall-growing plants, resulting in increased shading and biomass accumulation at the soil surface. The decline in ground-level insolation is a key mechanism by which N pollution causes species loss (Hautier, Niklaus & Hector 2009), with small-growing species under most threat (Hodgson *et al.* 2014). Nitrogen is also an acidifying pollutant, whether deposited in oxidised or reduced form. With the ongoing decline in sulphur pollution, N now makes up around 90% of acidity pollution in the UK (Rowe *et al.* 2022). Nitrogen gases such as ammonia can also be toxic for many species, and lichens and bryophytes can be particularly sensitive as they rely directly on the air and rain for their nutrients and have no waxy surface to control uptake of N. Combinations of pollutants may increase the impacts of N pollution, with additive impacts from for example NO_x and NH_3 (Sutton *et al.* 2022).

Much evidence for N effects on ecosystems relates to the occurrence of plant and lichen species (Phoenix *et al.* 2012), or to biogeochemical changes such as soil N availability (Rowe *et al.* 2012; Leith *et al.* 2005), assessed in field experiments or survey data. In uncontrolled experiments and surveys, it can be difficult to separate out the effects of N pollution from those of other factors such as decreased biomass removal, drainage, climate change, or disturbance. A 2017 review of metrics for evaluating ecosystem changes in response to declining N pollution (Rowe *et al.* 2017) concluded that the most relevant were those based on a) traits of the plant and lichen assemblage such as occurrence of distinctive species for the habitat or [forb / total] cover, b) N concentration in moss tissue, and c) N concentrations in leachate. More evidence has emerged recently, particularly for N impacts on animals (Ross in press). However, few studies have measured ecosystem changes following a decrease in N addition.

To better understand ecosystem recovery, it will be necessary to obtain evidence from a range of situations where N inputs have declined. For example: where experimental additions under reasonably controlled conditions in field experiments have ceased; in repeat surveys in areas where total N deposition has declined over time; or where a nearby emissions source has been closed and there are monitoring results spanning the potential recovery period. Confidence in such evidence will be greater where potential confounding factors can be characterised, have been stable, or can be accounted for using an appropriate experimental design.

Predictive modelling is an important aspect of the assessment of recovery from atmospheric N pollution. Modelled estimates of the background rate of N deposition are necessary for interpreting the results of field additions. Studies of the effects of removal of emissions sources depend on modelling N deposition or gas concentrations before and after the change. Methods for modelling atmospheric chemistry are well-established. Ecosystem responses are relatively complex, although predictive models are available of biogeochemical change and of responses of plant and animal species. The workshop could consider the role of atmospheric and ecosystem models in establishing an evidence base for recovery from N pollution.

The UK includes a wide ecological range. Areas of certain UK habitats may be internationally important or locally significant or may support species in need of protection. Conversely, some habitats and species are less threatened. During the workshop, a shortlist will be developed of habitats where N impacts are particularly relevant.

We anticipate discussion around the following **themes**:

- **What constitutes species/habitat/ecosystem recovery in an era of multiple stressors and/or contexts?**

This could include discussion of appropriate targets, informed by theoretical and practical developments in conservation biology and restoration ecology. Recovery pathways may differ depending on the abiotic context (e.g. soil pH) and/or the biotic context (e.g. presence of grazers) - in the same way that empirical critical loads can be dependent on context. Additional drivers may change the endpoint/recovery pathway. Recovery pathways may differ from impact pathways (i.e. there may be hysteresis).

- **What would make a good recovery indicator and why?**

This could include discussion on ease of measurement, robustness, transferability, and so forth. Are there differences depending on whether it is ecosystem, habitat or species recovery that is being considered? Can a change in an indicator be clearly linked to a driver that is declining, whether that decline is modelled or measured? Do sessile organisms such as plants make better indicators than mobile organisms? Is it better to consider pollution-sensitive, charismatic, or functionally important taxa? How does measurement uncertainty affect the timescale over which the change can be detected?

- **What are the specific indicators for recovery from atmospheric N pollution?**

Particular indicators may respond to N more than to other stressors – for instance, specific species, functional groups, or community signatures such as mean Ellenberg N or other functional traits. Is it sensible to consider scarce species as indicators of recovery? Can recovery be expected in all places, given ongoing ammonia pollution? Do different forms of

N lead to alternative recovery pathways? We can also discuss whether indicators capture recovery from both eutrophication and acidification, can capture recovery from sustained deposition or high atmospheric concentrations, and can consider the timescale of persistence.

- **What are the established methods for assessing N impacts and recovery?**
- **What novel methods are promising?**

These two themes could consider both empirical and modelling approaches.

- **Conceptually, what types of studies are useful for evidence of recovery?**
- **What specific sites from around the UK could be used to obtain evidence for recovery?**

These two themes provide the opportunity to consider the types of studies, for example the cessation of N addition in experiments or the closure of emission sources. Participants may want to highlight sites where Phase 2 work could be carried out.

Outcomes

Following the workshop, UKCEH and JNCC will capture the discussions in a brief report and circulate this to participants with requests for comments. We will then compile a final report, including a summary of advice on the future phases of the APRI project; lists of key habitats and species for which pollution recovery indicators are feasible; a summary of existing networks and projects that could provide information about pollution recovery; and advice on knowledge gaps and future evidence requirements.

Appendix: 4 Workshop Summary

The workshop was held in a hybrid format to maximise potential participation, over 7–8 November 2023. Those attending in person met at The Royal Botanic Gardens Kew in the Herbarium.

Overall, 27 participants (19 in person, 8 online) were involved over the two days, from across policy, non-governmental, and the scientific research communities, including universities and research centres, from the UK and internationally. Participants at the workshop were invited based on previous work on air pollution and/or ecosystem recovery, with recommendations submitted by the organising team.

The workshop was held under the Chatham House rule (i.e. that statements would not be attributed to individuals), to encourage free discussion. The workshop was carefully facilitated to ensure that all attendees, including those online, were able to participate and have their views represented. A combination of plenary and small-group work was undertaken to facilitate discussion, with seven short talks providing different perspectives.

The full **Workshop Abstracts** for the perspective talks, are included in Appendix 2: Workshop Abstracts. Unfortunately, Frank Gilliam was unable to attend the meeting, but we have retained his abstract. Participants were provided a **Background Document** prior to the workshop (Appendix 3: Workshop Background Document). This Background Document provides a brief introduction to nitrogen impacts on ecosystems and some elements of recovery science.

The workshop began with brief introductions from Paul Wilkin (Head of Ecosystem Stewardship, RBG Kew), Dave Stone (Chief Scientist, JNCC) and David Vowles (Senior Policy Advisor, Air Quality and Industrial Emissions, Defra). This was followed by a joint presentation from Susan Zappala (JNCC) and Ed Rowe (UKCEH) summarising the workshop aims (i.e.) **the development of an indicator or set of indicators to allow understanding of ecosystem and species recovery in response to policies to reduce atmospheric pollution, specifically nitrogen.** In addition to this main aim, Susan and Ed also highlighted the need to consider **the various habitats to which indicators could be applied**, and **what sort of evidence may be useful to consider in developing a framework for Phase 2**.

The first presentation of the workshop was given by the Phase 1 APRI team at Royal Botanic Gardens Kew (RBG Kew) and the Natural History Museum (NHM), including *Jill Kowal*, *Elena Arrigoni*, *Laura Martinez-Suz* (all at RBG Kew) and *Silvia Pressel* (NHM). They highlighted findings from a global survey that showed ectomycorrhizae were sensitive to nitrogen deposition (van der Linde *et al.* 2018), with the potential to indicate tipping points (Suz *et al.* 2021), noting that these ideas need mechanistic testing. They then presented recent work from Thursley Common (a former UKREATE heathland site – see Existing Experiments). This included pointing towards a forthcoming paper on recovery indicators at Thursley following the cessation of N addition, led by Jill Kowal, and their experimental plan to assess recovery from N deposition following a controlled burn. This experiment will involve addition of N after the burn, to be conducted over the next year, with cessation of this addition once a stress response is observed.

Andrea Britton (James Hutton Institute, JHI) provided a summary of findings from Scotland in regard to the NINE project: Nitrogen Impacts in Natural Ecosystems. In particular, Andrea highlighted the overarching aim of the NINE project: ‘To develop understanding of impacts of N deposition on sensitive natural ecosystems in Scotland in the context of climate change and other drivers’ with three main foci: (i) N-by-climate impacts on Scottish ecosystems; (ii) Methods for mitigation of N impacts; and, (iii) Indicators and metrics for recovery from N impact. Many of the findings from their report (Britton, Fielding, and Pakeman 2023) informed this summary, but of note are (Scottish) knowledge gaps around (i) rocky habitats, alpine habitats, and scrub and wetland in relation to critical N loads; and (ii) impacts of N on belowground biodiversity and above-ground fauna. In regards to recovery indicators, key findings were: (i) evidence for natural recovery in several habitats with relatively quick (months – years) recovery of soil parameters but slow recovery of biodiversity (decades); (ii) management actions may help with recovery from N impacts but few tests generally, with hardly any in Scotland; (iii) vegetation and soil parameters have been linked to N deposition but few have been fully tested as indicators and none are included in Scottish statutory monitoring; (iv) many indicators perform best in a particular habitat. Both (i) and (iv) suggest that baskets of indicators will be required to cover all habitats and timescales. Regarding novel methods, the final key finding was that remote sensing, drone-based surveys and eDNA have potential as monitoring methods but they need development.

Mike Perring (UKCEH) outlined research demonstrating the importance of cumulative N deposition for understanding ecosystem and species impacts and the importance of hysteresis (history dependence). Where hysteresis is present in complex systems, there will be different recovery pathways to those of impact, with the potential for different indicators of recovery from air pollution; he then showed a specific example of this history dependence in relation to N deposition in North American grassland (Meyer *et al.* 2023). Finally, he presented some conceptual figures and tables from the International Principles and Standards for Ecological Restoration (Gann *et al.* 2019) which suggest how to quantify recovery pathways while accounting for multiple indicators. Together, Mike's presentation suggested different indicators may respond on different timescales and emphasized the need for a basket of indicators, which was reinforced in subsequent discussions.

Jeff Duckett (QMUL) presented work showing how presence-absence records for moss species suggest recovery of epiphytic species from historical air pollution around London. However, he also highlighted the fact that there are lots of suggestions for why these dynamics are observed, but ideas are rarely tested.

The final perspective in the first day's afternoon session came from *Matt Jones* (UKCEH) who presented findings from the Whim Bog Experiment (and recent extensions to elsewhere in Scotland, and Sri Lanka), noting the different response of systems to nitrogen in the gaseous ammonia form, and that from the same amount of N addition but via wet deposition. This presentation suggests that the form of N needs accounting for and may affect recovery pathways as well as the 'starting' point of recovery.

Two more perspectives were presented the following morning: *Hannah Risser* (UKCEH) highlighted the mechanisms by which butterfly populations may be indirectly affected by N deposition (e.g. altered microclimate, changed food plant availability), and how broad-scale survey evidence indicates correlations of N and mid- and late-season temperatures with population dynamics of certain species. More broadly, N deposition seems to be linked to winner and loser species, with the potential for these to be linked to butterfly traits, making butterflies a potentially useful indicator species group for recovery. Hannah noted that there will be forthcoming work, funded by JNCC, extending these analyses to moths.

Laurence Jones (UKCEH) presented the final perspective, noting the potential for the former UKREATE sites to contribute to understanding of recovery from atmospheric N pollution, especially given the large amount of historical data associated with potential indicators, and the fact that some former UKREATE sites have ceased to add nitrogen.

Between the two perspective sessions, the workshop split into two groups in person, with a further group online, to discuss the following questions:

- What constitutes species/habitat recovery in an era of multiple stressors?
- Is the type of pressure from N (ammonia concentration, N deposition etc.) important?
- Where can we get good evidence to help understand damage and recovery? Beyond the UK?
- What would make a good recovery indicator and why?

Each subgroup then reported back in plenary. These discussions are not reported in full, but pertinent aspects are noted in relevant sections to the main Report.

After the second perspective session, a plenary discussion was held regarding the following questions:

- What are the specific indicators for recovery from atmospheric N pollution?
- What are the established methods for assessing N impacts and recovery?
- What novel methods are promising?
- What types of studies are conceptually useful for evidence of recovery?
- What specific sites should be used to obtain evidence for recovery?

As before, these discussions are not reported in full herein, but important aspects feature in our recommendations.

The final session then discussed the following questions, as we moved towards concrete recommendations and away from the more open debate of the previous plenary discussions:

- Which recovery indicators?
- Which habitats?
- Which ecosystems within the habitat?
- Which taxa?
- Which methods?