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Detecting and attributing air pollution impacts during SSSI condition assessment

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Contents

1 Summary

1. The most recent assessments of the effects of air pollution on semi-natural habitats in the UK, using critical loads, show that a substantial area is at risk from either acidification or eutrophication. There is a demand for doing more within the current common standards monitoring (CSM) framework to attribute air pollution (particularly nitrogen deposition) as a cause of unfavourable condition and to ensure that for sites which are being adversely 'impacted' by air pollution this is recorded. This report makes recommendations for how detection and attribution of N deposition can be incorporated into CSM monitoring and the indicators that would be needed to do this.

2. A number of habitats have been identified as both sensitive and vulnerable to acid deposition, including heathland, bog and grassland habitats. This report will focus on:

    - acid grassland (lowland dry acid grassland, upland acid grassland);
    - bogs (raised bogs, lowland blanket bog, blanket bog and valley mire);
    - heathland (lowland heathland, subalpine dry dwarf-shrub heath, wet heath);
    - woodlands.

    These habitats are amongst the most sensitive and vulnerable to nitrogen (N) deposition. They are also widespread habitats that occur in many SSSIs.

3. Across the investigated habitats, few of the existing CSM site condition indicator species were suitable for determining the impact of N deposition on a site. More evidence is needed on the impacts of N deposition on individual species.

4. In acid grassland, canonical correspondence analysis of existing survey data from acid grasslands failed to find any species for which presence / absence data were sufficient to identify an impact of N deposition. The most promising indicators of N deposition were other variables, such as species richness and cover. Of the variables investigated, the best indicators of N deposition were species richness, forb richness and graminoid:forb ratio (based on % cover).

5. In bog communities, a number of potential indicator species were identified using canonical correspondence analysis. A list of positive indicator species was identified, which could be used to indicate positive site condition in response to N deposition. A second possible indicator was that less than five percent of vegetation cover should consist of either *Vaccinium myrtillus* or *Polytrichum commune*.

6. Data from a regional survey and several long-term experiments were used to identify potential indicators for N deposition in heathlands. Total plant species richness was negatively correlated with regional nitrogen deposition, and bryophytes were the group most indicative of change. On upland dry heath, several potential indicator bryophyte species were identified but the best negative indicator of N deposition was the combined frequency of *Hylocomium splendens* and *Dicranum scoparium*. Further research is needed to determine whether these indicators would be suitable in lowland heathlands.

7. For woodlands, literature review was used to identify indicators of N deposition, particularly the national survey conducted by Kirby *et al* (2005). Several potential indicators of N deposition were identified but the variability between woodland types makes it difficult to identify indicators that will be suitable in all habitats.

8. Proposed indicators are summarised in the table below:

Habitat	**Attribute**	**Target**	**Method of assessment / Comments**
Acid Grassland	Impact of nitrogen deposition	Graminoid:forb ratio should be less than 5	Target assessed against visual estimate of % cover for graminoids (grasses, sedges and small rushes, such as *Luzula* spp.) and forb at a 4m^2 scale. Graminoid cover should then be divided by forb cover. Five estimates should be made spread throughout the site and an average values estimated for the site.
Bogs	Impact of nitrogen deposition	Presence of positive site condition indicator species Less than 5% of vegetation cover should consist of either *Vaccinium myrtillus* or *Polytrichum commune*	The presence of three of the following seven species indicates positive site condition: *Drosera rotundifolia* *D. intermedia* *Pinguicula vulgaris* *Polygala serpyllifolia* *Dactylorhiza maculata* *Pedicularis sylvatica* *Hylocomium splendens* Target assessed against visual estimate of % cover at a 4m^2 scale. Five estimates should be made spread throughout the site and an average values estimated for the site.
Heathland	Impact of nitrogen deposition	The combined frequency of *Hylocomium splendens* and *Dicranum scoparium* should be more than 0.5	Target assessed against presence or absence in five randomly placed 0.25m^2 areas to give a combined frequency score
Woodland	Impact of nitrogen deposition	No indicators recommended	

9. N deposition cannot be attributed as a cause of vegetation change using indicators alone as many of the indicators of N deposition would also be impacted by

management. It is important that other sources of N enrichment and changes in management are identified.

10. Management is a potential confounding factor and may lead to similar changes in vegetation composition to N enrichment by deposition. However, for all of the habitats considered, a wide range of management intensities and strategies were encompassed through the large number and variety of surveyed sites so much of this variation is already considered in the analysis.

11. The additional information gained from incorporating the suggested indicators for acid grassland, heathland and bogs into CSM guidance would provide an evidence base for policy regarding the impacts of N deposition and offers advancement from the current situation. As the suggested indicators are similar to those already in use the cost of incorporating them will be minimised.

12. For woodlands the lack of division between woodland habitats for CSM guidance makes it difficult to identify suitable indicators for detecting and attributing N deposition.

13. Further research and testing is required to be sure that there is a high degree of confidence in the results before incorporating indicators and source attribution questions into guidance. Testing of these indicators could be conducted using existing data sources such as NVC surveys and ESA monitoring data, but it is important that the limitations of such ‘snap-shot’ surveys are considered when interpreting the data and that consistent methods are used in the assessment of sites.

14. We conclude that there is potential for the detection and attribution of air pollution impacts within the CSM framework (for the habitats considered); alternative options have therefore not been considered in this report. New indicators could be inserted into the existing CSM framework. Options for testing and evaluating these indicators to ensure an effective evidence base for policy are provided in section 5 but for a full assessment of air pollution impacts we would propose using a two-tier method, using a combination of CSM and biogeochemical sampling.

15. A two-tier method of assessing the impact of N deposition on SSSIs, with CSM providing an initial indication of habitats that are likely to be impacted by N deposition and more detailed biogeochemical analysis to provide greater certainty and the degree of impact. Results could be compared to reference vegetation stands. Additionally further analysis of Countryside Survey data could be used to identify trajectories of change that can be attributed to N deposition impacts.

2 Introduction

The most recent assessments of the effects of air pollution on semi-natural habitats in the UK, using critical loads, show that a substantial area is at risk from either acidification or eutrophication. The conservation agencies' monitoring of SSSI condition is based on Common Standard Monitoring (CSM) guidance http://www.jncc.gov.uk/page-2219. CSM provides a basic framework to ensure consistent monitoring in the UK. The main purpose of site assessment is to:

- determine whether the desired condition of the feature(s) of interest for which the site was designated is being achieved. This can enable judgements to be made about whether the management of the site is appropriate, or whether changes are necessary;
- to enable managers and policy makers to determine whether the site series as a whole is achieving the required condition, and the degree to which current legal, administrative and incentive measures are proving effective.

CSM is not designed to assess and attribute drivers of environmental change such as air pollution impacts. In order to get a good understanding of cause and effect of air pollutants on site condition, much more detailed assessment is required, along with comparison between sites, than is possible within the CSM framework. However, as a result, it is acknowledged that CSM is likely to fail to detect and attribute the effects of air pollution in a consistent and auditable manner. Therefore, it is very likely that we are under-reporting the impacts of air pollution. This is of major concern since it presents a very mixed message to stakeholders and ultimately could serve to undermine the policy drivers for action on air pollution emissions.

However, both the assessment of impacts and the attribution of air pollution as a contributory cause of unfavourable condition of terrestrial SSSIs are extremely challenging. Often, air pollution effects will be as a result of complex interactions with other abiotic or biotic stresses, for example climate and grazing. In addition, the impacts of chronic exposure to air pollution may take many years to be manifest; conversely on some sites, soils and habitats may already (and at the time of notification) be affected by historical pollution. As a result a site may be:

- reported as 'favourable', but air pollution is currently having an adverse impact (and monitoring is not 'sensitive' enough to detect);
- site reported as 'favourable', but air pollution likely to adversely effect in future (time lag in response);
- site reported as 'unfavourable', and air pollution is a contributory cause, but it is not recorded as such.

Whilst it should be possible to distinguish air pollution impacts at sites where there is a major effect using CSM (although noting in practice this is not always achieved), for sites where there are more chronic impacts interacting with a range of other ecological drivers of change it is impossible, within the current monitoring framework and objective, to consistently detect and attribute air pollution impacts.

Because of these limitations, over the last few years JNCC and the country conservation agencies have been exploring ways to improve the evidence base of air pollution impacts on protected sites. It is proposed to undertake:

- a risk assessment of all SSSIs based on critical load exceedance so that risk from air pollution can be reported alongside site condition;
- more intensive monitoring on a subset of sites, to detect air pollution impacts or more effective use of existing surveillance data to detect and attribute an effect more widely.

However, there remains demand for doing more within the current CSM framework to attribute air pollution (particularly nitrogen deposition) as a cause of unfavourable condition and to ensure that for sites which are being adversely 'impacted' by air pollution this is recorded. This represents a scientific and practical quandary: on the one hand we recognise that the CSM approach is not designed for this purpose and therefore has many limitations in this respect; on the other hand it is considered that we should at least be able to improve on the current situation by better use of indicator species within the CSM guidance, particularly for habitats with a well characterised response to air pollutants.

The primary objectives of this project are:

- to explore the potential, within the existing framework of CSM (for sensitive terrestrial habitats), to attribute air pollution as a cause of unfavourable condition;
- to identify and evaluate indicator species (in terms of presence/absence, cover or change in abundance etc) for sensitive habitats;
- to critically examine whether, in the context of a requirement to provide an evidence base for policy and casework advice, this offers a sufficient advancement from the current situation.

The primary focus is therefore on the scope for detection and attribution of air pollution impacts within the constraints of the existing CSM framework. A secondary objective of the project is:

- to provide broad recommendations for how the different options should be evaluated in order to deliver an effective evidence-base for informing policy.

3 Which habitats are potentially sensitive to nitrogen (N) deposition?

Characteristics of habitats can make them potentially sensitive to atmospheric acid and nutrient deposition. Habitats with weakly buffered soils (low pH) are most sensitive to acidification. Habitats most likely to be sensitive to eutrophication include those with low levels of nutrients in their soils, those dominated by stress tolerant species and those that depend on atmospheric inputs as their primary source of nutrients. For the purposes of this discussion sensitivity is defined as the responsiveness of the system and vulnerability is defined as the likelihood of response given current deposition levels and habitat distribution. For example a habitat is sensitive to N deposition if it changes as a result of it but if it is only found in areas of low N deposition we would not consider it to be currently vulnerable to N deposition.

A brief discussion of the sensitivity and vulnerability of terrestrial habitats outlined in the CSM guidance to atmospheric acid deposition is given below.

3.1 Coastal

- **Coastal vegetated shingle** – Shingle vegetation is a pioneer community composed of many nutrient loving ruderal species. Close to the sea the nutrients are mainly supplied by organic matter deposited by the sea. This community is unlikely to be sensitive to atmospheric N deposition as the supply of nutrients is primarily driven by the sea. Further away from the sea where communities have had longer to develop vegetation may be dry acid grassland or heath and sensitive to acid deposition.
- **Sand dunes** - A national survey of sand dune vegetation has demonstrated a negative relationship between plant species richness and atmospheric N deposition (Jones *et al*, 2004). Changes in species composition have also been observed and a number of species have been identified as being stimulated by atmospheric N deposition (van den Berg *et al*, 2005). This evidence indicates that sand dunes are sensitive to N deposition. The distribution of sand dunes in the UK means that some will be vulnerable to N deposition (i.e. in areas of high deposition).
- **Saltmarsh** – As with shingle vegetation, the impacts of nutrients on saltmarsh vegetation are mainly driven by the sea. Saltmarshes are inundated by tides on a regular basis which deposits nutrient-rich sediments and organic matter. Atmospheric deposition is unlikely to have a strong influence on this saltmarsh community. Moving slightly inland, the coastal and floodplain grazing marsh form some of the last remaining unimproved grasslands and are likely to be highly sensitive to eutrophication (UKBAP, 2008)
- **Maritime cliff and slope** – Maritime cliff communities can be very variable due to geology, climate and exposure to sea spray. There is potential for sites to be impacted by acid deposition where the soil type is poorly buffered against acidification, and vegetation communities are nutrient poor. However, this is likely to be subordinate to the impacts of sea-spray where sea spray has an important influence.

3.2 Lowland grassland

- **Lowland meadows and upland hay meadows** – Hay meadows generally contain a minority of species typical of fertile environments (Ellenberg fertility score (Hill *et al*,

1999) of greater than 5) and experimental additions of low level of N have been shown to rapidly encourage the spread of agriculturally productive grasses in an MG5 grassland (Mountford *et al*, 1993). Soils of these mesotrophic grasslands are unlikely to be severely impacted by acidification. Occurring in areas of high acid deposition, such as central and northern England, it is likely to be a vulnerable community.

- **Lowland calcareous grassland** – Grasslands on calcareous soils are unlikely to be sensitive to acidification because the soils are well buffered against change but in many of these communities the vegetation is adapted to low nutrient levels. Low level experimental N additions have shown potential for increased productivity and changes in species composition (Wilson *et al*, 1995) where the grassland is N limited. Surveys have shown that slope and aspect are likely to have an important influence over the sensitivity of the grassland to eutrophication (Bennie *et al*, 2006). Phosphorus limited grasslands (which many calcareous grasslands are thought to be) are unlikely to be sensitive. These grasslands are potentially vulnerable to N deposition as some occur in areas of high inputs.
- **Lowland dry acid grasslands** – These grasslands are very sensitive to both acidification and eutrophication. The soils are poorly buffered against changes in pH and toxic metals are commonly mobilised. The majority of species are typical of infertile environments (Hill *et al*, 1999). Evidence using national gradients (Stevens *et al*, 2004; Stevens *et al*; 2006) show sensitivity to changes even at low levels of N deposition and evidence of acidification from S deposition. This demonstrates that these grasslands are vulnerable to N deposition. Experimental N additions in the Peak District have also demonstrated changes in species composition and soil chemistry (Morecroft *et al*, 1994; Phoenix *et al*, 2003).
- **Lowland purple moor grass and rush pastures** – The National Vegetation Classification (NVC) (Rodwell, 1992) communities that make up this group are likely to show a varied sensitivity. Those communities that depend on flushes or overland flow and found on base-rich soils (such as the fen-meadow community M22) are likely to be less sensitive to acid deposition than those that are more rain-fed or have acid soils such as M25. However, experimental N additions have shown the potential for change in species composition at high N inputs in calcareous fens (Bergamini and Pauli, 2001; Pauli *et al*, 2002). All of the communities can occur in areas of high deposition meaning they are vulnerable to N deposition. In some situations conversion of heathland to *Molinia* grassland is believed to result from eutrophication.
- **Lowland calaminarian grasslands** – This nutrient poor community is likely to be sensitive to acid deposition. The soils are typically calcareous meaning they are well buffered against changes in pH as a result of acidification but the characteristic species of this community are typical of very nutrient poor environments. This suggests that they are likely to be sensitive to eutrophication from N deposition. The distribution of these grasslands means that they are vulnerable to acid deposition.

3.3 Lowland heathland

- **Lowland heathland** – Heathland communities are very sensitive to acid deposition. The organo-mineral soils and stress tolerant vegetation mean they are sensitive to both acidification and eutrophication. The impacts of N deposition on heathland have been seen extensively in The Netherlands where grasses have become dominant and there have been declines in heather (*Calluna vulgaris*) cover (e.g. Heil and Diemont, 1983; Roelofs, 1986). In the UK experimental N additions at a level just above the critical load for N have shown changes in productivity, litter production, N cycling and lichens in lowland heath (Power *et al*, 1995; Power *et al*, 1998) but little evidence of grass invasion was seen unless disturbance accompanied N treatment (Caporn *et al,* 2007). The distribution of this community means that many areas are vulnerable to N deposition. The effects are suspected in some areas (eg Breckland) but the N deposition effect has not been demonstrated.

3.4 Lowland wetland

- **Raised bogs** – These ombrotrophic ecosystems receive all of their nutrient inputs from atmospheric sources. This makes them very sensitive to eutrophication by N deposition (Berendse *et al,* 2001). They also have peat soils that are sensitive to acidification (Skiba *et al,* 1989). Acid deposition can result in changes in species composition with increases in nitrophilous species and declines in other species including *Sphagnum* (Hogg *et al,* 1995; Baddeley *et al,* 1994; Pitcairn *et al,* 1991). These bogs are both sensitive and vulnerable to acid and N deposition.
- **Lowland blanket bog** – Blanket bogs will be impacted by N deposition in the same way as raised bogs (above). The location of lowland bogs means that many are vulnerable to N acid deposition. New research from the long-term (started 2002) N addition experiment at Whim bog, Midlothian (Sheppard & Leith unpublished presentation, November 2007) has demonstrated that of the three main species at this site, *Sphagnum capillifolium* was most negatively affected, *Erica tetralix* was most positively affected, *Hypnum jutlandicum* was also generally stimulated while *Calluna vulgaris* was least influenced by the raised N. The effect of the ammonium ion was generally greater than nitrate and additions of just 8 kg N ha^{-1} y^{-1} were typically effective in causing community change.
- **Flood-plain fens** – Flood plain fens contain a range of communities including those that are likely to be very sensitive to N deposition (such as bogs – see above). Other communities are nutrient rich and occur on well-buffered soils so are less sensitive to acid deposition. Communities that depend primarily on rain-water for nutrients are likely to be the most sensitive to atmospheric input whereas those that depend on overbank flooding are likely to be less sensitive.
- **Basin fens** – Basin fens encompass a wide range of communities which vary in their sensitivity to acid deposition. Those communities that are nutrient poor, rainwater fed or found on peat soils are likely to be the most sensitive. Calcareous fen communities may also be sensitive to acid deposition (Bergamini and Pauli, 2001; Pauli *et al,* 2002). Bog components will be very sensitive (see above) whereas spring-fed components will be less so (see below).
- **Valley fens** – As with basin fens, valley fens can contain a wide range of communities with varying sensitivity (see above).
- **Open-water transition fens** – Open-water transition fens may be more dependant on the water source (e.g. river flowing into a lake which the fen borders) than atmospheric inputs for their nutrients. Consequently the influence of atmospheric deposition is not likely to be strong. The key communities in this group are S4 and S8 which are dominated by indicators of fertile environments and are unlikely to be impacted by eutrophication. However, this group encompasses a range of NVC communities and those characterised by stress-tolerant vegetation or acid soils are likely to be the most sensitive to acid deposition.
- **Springs and flushes** – The plant communities of springs and flushes are likely to be more dependent on the pH and nutrient content of the water they receive in the spring

or flush than atmospheric deposition. Although they could be impacted by very high levels of acid deposition they are unlikely to be a very sensitive community.

- **Fen meadows** – See lowland purple moor grass and rush pastures. These two communities cover the same communities under the NVC.
- **Fen woodland** – As with fens, atmospheric acid deposition is likely to be a secondary driver to water chemistry. There is potential for negative impacts but this community has received very little research attention in relation to its response.

3.5 Woodland

Woodland – Woodlands vary considerably in their species composition and in their response to acid deposition (Dise *et al,* 2001). Studies throughout Europe have shown evidence for changes in soil chemistry (Dise and Wright, 1995), biomass (Nellerman and Thomsen, 2001) and changes in ground flora composition (Pitcairn *et al,* 1998). Crown discoloration and chlorosis is associated with high N deposition (Power *et al,* 1995). Woodlands on nutrient poor soils are most likely to be sensitive to N deposition. A national woodland survey (Kirby *et al,* 2005) in 2001, repeating a similar one in 1971 found there was no overall shift in species towards more fertile/eutrophic assemblages and no change in mean Ellenberg fertility score. Increasing soil pH and high levels of intensive land surrounding the wood were however associated with increases in Ellenberg fertility scores. The most N sensitive elements in woodlands are likely to be the epiphytes. Gadson (2007) found strong correlations between shifts in the twig lichen communities and the ambient dry N deposition in Epping Forest.

3.6 Upland habitats

- **Acid grassland** – Upland acid grasslands are very susceptible to the impacts of N deposition, even at low levels of deposition. Impacts include a reduction in species richness and a decline in forbs species richness and cover (Stevens *et al,* 2004). These impacts are discussed above for lowland acid grasslands. Upland acid grasslands are vulnerable to N deposition as even at low levels changes can be detected. The grasslands occur in all upland regions of the UK including those with the highest deposition.
- **Alkaline fen** – Highly calcareous and base-rich conditions make this community unlikely to be affected by acid deposition, but these species rich, often montane communities, are likely to be N nutrient-poor (as indicated by species such as the insectivorous *Pinguicula vulgaris)* and therefore vulnerable to N deposition.
- **Alpine dwarf-shrub heath** – Characteristic of base-poor soils on exposed mountain ridges and summits. The H13 *Calluna vulgaris-Cladonia arbuscula* heath vegetation is well researched in the Cairngorms (Britton *et al,* 2007) and experimental treatments of 10 kg N ha^{-1} y^{-1} above ambient have affected lichens and *Calluna*. The communities, including *Racomitrium lanuginosum* dominated communities, are known to be sensitive to N deposition (Baddeley, Thompson and Lee 1995; Pearce & Woodin, 2003).
- **Alpine flush** – Containing rare/scare vascular species, these communities of base-rich flushes should be tolerant of acid deposition but are probably N sensitive, as suggested by the presence of *Pinguicula vulgaris* in some areas.

- **Alpine summit communities** – Suffering wind exposure but various degrees of snow cover, these patchy moss, sedge, rush –dominated communities are also influenced by grazing and appear very sensitive to N deposition as shown in experiments in the Scottish Highlands (Pearce & van der Val, 2002).
- **Blanket bog and valley bog** – Upland blanket bogs and valley bogs will share the same sensitivity as their lowland counterparts (see above). They are likely to be vulnerable to acid and N deposition because although they are extensive in areas of low deposition, in other upland areas, such as the Pennines, they are subject to some of the highest deposition levels in the UK. The recovery, evident but slow, of *Sphagnum* communities on the South Pennine blanket bogs despite the continuing high N deposition indicates that certain species are relatively N tolerant (e.g. *S. cuspidatum, S. fallax*) but others are still rare and probably N-affected, particularly the important hummock types *S. papillosum* and *S. capillifolium* (Lee, 1998; Caporn *et al*, 2006). The more minerotrophic conditions of the valley bogs should mean these are less influenced by acid and N deposition in comparison with the ombrotrophic bog surfaces, but N deposition will most likely lead to increased graminoid competition (Hall *et al,* 2003).
- **Calaminarian grassland and serpentine heath** – These ultra-basic influenced communities are not likely to be acid deposition affected, but are probably N-poor and therefore N sensitive.
- **Calcareous grassland** - As in lowland calcareous grasslands (above), soils of upland calcareous grasslands are well buffered against pH change but vegetation is adapted to low nutrient levels. Whilst some grasslands are likely to be P limited, experimental N additions to upland calcareous grasslands in the Peak District have shown large changes in species abundance (Carroll *et al,* 2003). Therefore it is likely that these grasslands are sensitive to N deposition. Their distribution means that they are vulnerable to N deposition.
- **Calcareous rocky slope** – Ferns and mosses are the most common plants, growing out of crevices and cracks. Unlikely to be acid sensitive, the moss component will probably be vulnerable to N deposition.
- **Calcareous scree** – Similar to calcareous rocky slopes (above) but more prone to invasion from woody species.
- **Fellfield** – A variable type of community influenced more by the exposed environmental conditions than the substrate which varies from acidic to calcareous. Likely to be sensitive to N deposition and possibly acidity also depending on the substrate.
- **Fern-dominated snow-bed** – potentially affected by pulses of snow-melt acidity or N. This community usually occurs on base- and nutrient-poor soils so is potentially sensitive but its restricted distribution means it is not highly vulnerable.
- **Juniper heath and scrub** – This community is found on a variety of different substrates. There is currently no knowledge regarding its sensitivity to N deposition.
- **Limestone pavement** – Limestone pavements contain vegetation typical of both calcareous substrates, and, where organic matter has collected, acid substrates. The communities that occur in limestone pavements are typically in nutrient-poor conditions and are likely to be sensitive to N deposition. Some of the areas where limestone pavements are found experience high levels of acid deposition and so the communities found there are vulnerable to acid deposition.

- **Montane willow scrub** – Montane willow scrub is found on varying soils, rather undeveloped and skeletal, but usually with some degree of base enrichment. Therefore it is unlikely to be acid sensitive but may be prone to N enrichment.
- **Moss, dwarf-herb, and grass dominated snow-bed** – The moss /liverwort dominated snowbed communities are both sensitive and vulnerable to acidic and N deposition as found in Cairngorms by Woolgrove and Woodin (1996).
- **Short-sedge acidic fen** – This is a sedge dominated community with moderately base tolerant *Sphagna*. This community is probably sensitive to N deposition although less so than in ombrotrophic conditions.
- **Siliceous rocky slope** – Similar to calcareous rocky slope (above) but the poor buffering capacity means these will be prone to acidification as well as N eutrophication. They are likely to be vulnerable where they occur in areas of high deposition.
- **Siliceous scree** – Similar to siliceous rocky slope (above).
- **Soakaway and sump** – Soakaways and sumps are shallow waters over peats and peaty-mineral soils. The dominant species, *Hypericum elodes* and *Potamogeton polygonifolius*, are probably nutrient limited and thus may be sensitive to N deposition. Some occur in areas of high deposition and are likely to be vulnerable to acid deposition.
- **Spring-head, rill and flush** – These communities are found in flowing aquatic conditions of varying types ranging from acidic to basic conditions. These communities may be acid sensitive on the less buffered substrates, but there is little knowledge of acid deposition impacts.
- **Subalpine dry dwarf-shrub heath** - Long term additions of N to a Welsh upland dry heath (H12) community have demonstrated impacts on species composition, particularly a loss of bryophyte and lichen species, after as little as 10 kg N ha^{-1} y^{-1} above ambient (Carroll *et al,* 1999; Pilkington *et al,* 2007). Changes in the soil biogeochemistry and increased N leaching (especially after fire) have also been observed (Pilkington *et al,* 2005). Alonso *et al* (2001) demonstrated changes in upland heathland as a result of N increases but with management (grazing) also having a great impact.
- **Tall herbs** – The tall herb community is a rather variable community dominated mainly by tall herbaceous flowering plants. It can occur on both acid and calcareous substrates with those on calcareous substrates or with base rich flushing likely to be less sensitive to acidification. The dominant species of this community are not especially eutrophic so it may be sensitive to N deposition. It occurs in upland areas where there is protection from grazing. As these areas include some areas of high acid deposition it may be vulnerable to acid deposition.
- **Transition mire, ladder fen and quaking bog** – As with raised bogs (above) this bog community is oligotrophic and consequently sensitive to N deposition. It also has sensitive peat soils. The distribution of this community means that some are likely to be vulnerable to N deposition.
- **Wet heath** – As with other heathland communities (above) wet heath is likely to be sensitive to atmospheric deposition. The species composition is typically greater and more varied than many of the other heath communities, and is therefore probably sensitive to N deposition. Many of the species of these communities are typical of infertile environments (Hill *et al,* 1999). The location of these heathlands combined with their sensitivity means they are likely to be vulnerable to N deposition.

- **Yellow saxifrage bank** – This community is found on steep, continuously irrigated, calcareous slopes. The calcareous substrate means it is unlikely to be sensitive to acid deposition but the dominance of herbs suggests it may be sensitive to nutrient enrichment although enrichment of the water source would have a more severe impact. This species has a limited distribution but does occur in some areas of moderate to high deposition so may be vulnerable.

The CSM habitats we have selected for research in more detail are as follows:

- acid grassland (lowland dry acid grassland, upland acid grassland);
- bogs (raised bogs, lowland blanket bog, blanket bog and valley mire);
- heathland (lowland heathland, subalpine dry dwarf-shrub heath, wet heath);
- woodlands.

These habitats are especially sensitive and vulnerable to N deposition. They are also widespread habitats that occur in many SSSIs. Other habitats sensitive and vulnerable to N deposition such as montane heaths could merit similar work but this was not feasible within the current project.

4 Are species indicators in existing CSM guidance suitable for detecting and attributing air pollution?

For each of the selected habitats the existing CSM guidance (JNCC, 2004a, b, c, 2005) for positive and negative site condition indicators have been examined to identify whether they can be used to detect and attribute impacts of nitrogen deposition using review of the scientific literature, comparison with local and national data sets, ecological floras and Ellenberg values to evaluate positive and negative indicators. In this section the term 'evidence' refers to peer-reviewed literature. Responses to both eutrophication and acidification are considered as acidification is clearly related to N deposition but only responses to N deposition are considered, e.g. eutrophication from other sources is not considered. Indicators are also assessed with regard to JNCC requirements *i.e.* indicators need to be specific, easy to attribute to cause, quick to respond or robust early warning indicators, easy to identify and related to the feature of interest. Indicators are habitat specific as species may respond differently in different habitats.

Positive site condition indicators could be described as indicators of lower levels of nitrogen deposition. Negative site condition indicators are indicators of higher levels of nitrogen deposition.

4.1 Acid grassland

4.1.1 Lowland dry acid grassland (JNCC, 2004a) – Positive site conditions indicators

- ***Aira* spp.** – Ellenberg values (Hill *et al,* 1999) identify *Aira* as species of infertile habitats. They are also poor competitors with tall perennials (Sinker *et al,* 1991) which may be promoted by eutrophication. Grime *et al* (2007) identify *Aira* spp. as stress tolerant ruderals. Although these species are restricted to low nutrient habitats there is no evidence in the literature that they are impacted by N deposition. Consequently separating a response from other sources of eutrophication would not be possible without further research.
- ***Anemone nemorosa*** – Although *A. nemorosa* has been found to decline in experimental N addition in woodland (Falkengren-Grerup, 1993), there is no evidence from grassland. It has an Ellenberg value of intermediate nutrient status (Hill *et al,* 1999) and is not common in acid grasslands (Grime *et al,* 2007) making it unsuitable as an indicator of N deposition.
- ***Agrostis curtisii*** – *A. curtisii* has an Ellenberg value indicating it is a species of infertile habitats (Hill *et al,* 1999) but there is no evidence in the literature that it is impacted by N deposition, possibly due to its restricted distribution. Therefore it is not a suitable indicator of N deposition.
- ***Aphanes* spp.** – These species can be found in medium to rich nutrient status soils (Sinker *et al,* 1991; Hill *et al,* 1999) and can be weeds of arable land (Grime *et al,* 2007) so are not suitable as indicators of N deposition.
- ***Astragalus danicus*** - Although this species is restricted to low nutrient habitats (Hill *et al,* 1999) there is no evidence in the literature that it is impacted by N deposition. Consequently separating a response from other sources of eutrophication (e.g. fertilisation) would not be possible.
- ***Calluna vulgaris*** - *C. vulgaris* is perhaps one of the best investigated species with regard to N deposition. N addition experiments have identified a reduction in *C.*

vulgaris cover as a result of competition with grasses (e.g. Heil and Diemont, 1983), increased frost sensitivity (Carroll *et al*, 1999, Caporn *et al,* 2000), winter desiccation (Sheppard and Leith, 2002) and increased susceptibility to heather beetle (*Lochmaea suturalis*) attack (Brunsting and Heil, 1985). Nitrogen addition usually causes increased growth, however, in situations where it is dominant (Carroll *et al,* 1999). Stevens *et al* (2004) also identified this as a species that showed declines along the UK gradient of N deposition in acid grasslands. This is a potential indicator of N deposition.

- ***Campanula rotundifolia*** - *C. rotundifolia* is a species of infertile habitats (Preston *et al,* 2002; Hill *et al,* 1999) and is described as intolerant of competition with vigorous grasses (Sinker *et al,* 1985). Stevens *et al* (2004) identified this as a species that showed declines along the UK gradient of N deposition. This is a potential indicator of N deposition.
- ***Centaurium erythraea*** - This species is found at low nutrient levels (Hill *et al,* 1999), but mainly at a soil pH of greater than 5.5 (Grime *et al,* 2007). This means it is not suitable as an indicator of N deposition.
- ***Centaurea* spp.** - This genus is found at intermediate nutrient levels (Hill *et al,* 1999), and can be found in arable habitats (Preston *et al,* 2002) making it unsuitable as an indicator of N deposition.
- ***Cladonia* spp.** – Some *Cladonia* species have been shown to decrease in their cover with N addition in heathland (Britton and Fisher, 2007) however, responses differ between species so as a group this is not suitable as an indicator of N deposition (Pilkington *et al,* 2007). Individual species such as *C. portentosa* were sensitive in nitrogen experiments in upland dry heath (Caporn – unpublished observations) and at Whim lowland bog (Sheppard & Leith, unpublished).
- ***Dianthus deltoides*** – This species has a low Ellenberg value (Hill *et al,* 1999) but there is no evidence relating it to N deposition.
- ***Erica cinerea*** - *E. cinerea* has an Ellenberg value indicating it is a species of infertile habitats (Hill *et al,* 1999) although Grime *et al* (2007) describe it as a species of low or intermediate productivity. In controlled laboratory experiments it has shown increases in biomass production (Leith *et al,* 1999) suggesting complex responses to nutrients and that it is not suitable as an indicator of N deposition.
- ***Erica tetralix*** – *E. tetralix* is generally a species of low nutrient status soils (Hill *et al,* 1999; Sinker *et al,* 1985) but it can also grow in mesotrophic or eutrophic conditions (Preston *et al,* 2002). It is found primarily in wet soils (Grime *et al,* 2007). It has been identified in experiments as limited in its growth by nitrogen (Roem *et al,* 2002): and new data from Whim lowland bog showed strong positive responses to ammonium-N additions (Sheppard & Leith, unpublished). Further research is needed before it can be determined it this species is suitable as an indicator of N deposition.
- ***Erodium cicutarium*** - This species is found at intermediate nutrient levels (Hill *et al,* 1999; Sinker *et al,* 1985). This means it is not suitable as an indicator of N deposition.
- ***Galium saxatile*** – This species is described by Preston *et al* (2002) as a useful indicator of unimproved grasslands, however it has an Ellenberg value indicative of intermediate nutrient status (Hill *et al,* 1999). Despite frequently occurring in a survey of acid grasslands in relation to N deposition there was no evidence to indicate that *G. saxatile* responded to N deposition (Stevens *et al,* 2004).
- ***Galium verum*** – *G. verum* is a species of infertile habitats (Hill *et al,* 1999) and is not tolerant of competition with vigorous grasses promoted by N deposition (Sinker *et al,*

1985; van den Berg, 2005). It occurs in a wide range in grassland habitats but further research is needed to determine whether it would be a suitable indicator of N deposition.

- ***Genista tinctora*** - Although this species is restricted to low nutrient habitats (Hill *et al,* 1999) there is no evidence in the literature that it is impacted by N deposition. Consequently separating a response from other sources of eutrophication would not be possible.
- ***Lathyrus linifolius*** - This species is found at intermediate nutrient levels (Hill *et al,* 1999; Sinker *et al,* 1985) and is strongly influenced by moisture (Sinker *et al,* 1985) and grazing (Preston *et al,* 2002). This means it is not suitable as an indicator of N deposition.
- ***Leontodon taraxacoides*** – *L. taraxacoides* species is found at intermediate nutrient levels (Sinker *et al,* 1985). This means it is not suitable as an indicator of N deposition.
- ***Lotus corniculatus*** - *L. corniculatus* is a species of nutrient-poor habitats (Hill *et al,* 1999; Sinker *et al,* 1985) and is not tolerant of the most acid soils (Sinker *et al,* 1985). It potentially forms N_2 fixing symbiosis so would be expected to be nitrogen sensitive. Stevens *et al* (2004) identified this as a species that showed declines along the UK gradient of N deposition. This would suggest that it may be suitable as an indicator of N deposition.
- ***Orchidaceae* spp.** – Responses of species within this group to nutrient enrichment vary quite a lot so as a group it is not suitable for use as an indicator of N deposition.
- ***Ornithopus perpusillus*** - *O. perpusillus* is found at intermediate nutrient levels (Hill *et al,* 1999) and is strongly influenced by moisture (Preston *et al,* 2002) so is not suitable as an indicator of N deposition.
- ***Pedicularis sylvatica*** – Despite a low Ellenberg value (Hill *et al,* 1999) the restriction of this species to moist to damp peat means this species is not a suitable indicator of N deposition in dry acid grasslands.
- ***Pilosella officinarum*** – *P. officinarum* has a low Ellenberg value (Hill *et al,* 1999) but it is found in more nutrient rich habitats and across the whole country (Preston *et al,* 2002) suggesting it is not very sensitive to N deposition. It is also part of a taxonomically difficult group, making it less suitable for use as an indicator.
- ***Pimpinella saxifraga*** – *P. saxifraga* is commonly suppressed in fertilised grassland (Grime *et al,* 2007) and has a moderately low Ellenberg value (Hill *et al,* 1999). There is no evidence of a response to N deposition so further research would be required before impacts of N deposition could be separated from other types of fertilisation.
- ***Plantago coronopus*** – This species has an intermediate Ellenberg value (Hill *et al,* 1999) and there is no evidence relating it to N deposition.
- ***Polygala* spp.** – Responses of species within this group to nutrient enrichment vary (Hill *et al,* 1999) so as a group it is not suitable for use as an indicator of N deposition although individual species may be.
- ***Potentilla erecta*** – *P.erecta* is a characteristic species of nutrient-poor acid grasslands (Sinker *et al,* 1985) but is very tolerant of competition from vigorous grasses (Grime *et al,* 2007) which are promoted by N deposition. Despite frequently occurring in a survey of acid grasslands in relation to N deposition there was no evidence to indicate that this species responded to N deposition (Stevens *et al,* 2004).
- ***Rumex acetosella*** – *R. acetosella* has a moderately low Ellenberg score (Hill *et al,* 1999) and is not tolerant of competition with tall grasses (Sinker *et al,* 1985). It is a

colonist of bare ground on acid soil which may affect its suitability as an indicator of N deposition.

- ***Sanguisorba officinalis*** – This species is typical of habitats with medium to high nutrient levels (Hill *et al,* 1999; Sinker *et al,* 1985) but is not suitable as a positive indicator of N deposition impacts.
- ***Sedum acre*** – This species is found in very nutrient poor environments (Hill *et al,* 1999; Sinker *et al,* 1985) but is limited to skeletal, or virtually non-existent, acidic or basic soils (Preston *et al,* 2002) which may make it less suitable as an indicator in dry acid grasslands.
- ***Sedum anglicum*** – As with *S. acre*, *S anglicum* is found in nutrient poor habitats but is typical of open rock, mine spoil and old walls (Preston *et al,* 2002) meaning it may not be suitable as an indicator of N deposition in dry acid grasslands.
- ***Serratula tinctoria*** – *S. tinctoria* is a species of nutrient poor habitats (Hill *et al,* 1999; Sinker *et al,* 1985) but there is no evidence of it responding to N deposition or fertiliser addition.
- ***Stachys officinalis*** – This species has a low Ellenberg value (Hill *et al,* 1999) but there is no evidence relating it to N deposition.
- ***Succisa pratensis*** – *S. pratensis* has been shown in a laboratory experiment to have a reduced biomass at high ammonia concentration and low pH (van den Berg *et al,* 2005a) but there is no field evidence to show the response of this species in the field.
- ***Thymus* spp.** – Although all *Thymus* spp. have low Ellenberg values (Hill *et al,* 1999), T*hymus* spp have been shown to increase with experimental N addition in calcareous grasslands (Wilson *et al,* 1995) and to decrease in other experiments (Carroll *et al*, 2003). This would suggest it is not suitable as an indicator of N deposition.
- ***Teesdalia nudicaulis*** – This species has a low Ellenberg value (Hill *et al,* 1999) but there is no evidence relating it to N deposition.
- ***Teucrium scorodonia*** – *T. scorodonia* has an intermediate Ellenberg value (Hill *et al,* 1999). There is no evidence linking this species to N deposition.
- ***Vaccinium myrtillus*** – *V. myrtillus* has a moderately low Ellenberg score (Hill *et al,* 1999) and there is evidence of negative impacts of N deposition in forests (e.g. Strengbom *et al,* 2003). There is no evidence from grasslands to suggest that *V. myrtillus* is negatively impacted by N deposition.
- ***Veronica officinalis*** – This species has an intermediate Ellenberg value (Hill *et al,* 1999) suggesting it may not be very sensitive to N deposition.
- ***Vicia orobus*** – This species has an intermediate Ellenberg value (Hill *et al,* 1999) suggesting it may not be very sensitive to N deposition.
- ***Viola* spp.** – This group encompasses a number of species and responses to nutrient enrichment vary (Hill *et al,* 1999). As a group it is not suitable for use as an indicator of N deposition however, individual species may be.

4.1.2 Lowland dry acid grassland (JNCC, 2004a) – Negative site condition indicators

- ***Arrhenatherum elatius*** – *A. elatius* is a species of richly fertile habitats (Hill *et al,* 1999). Although it responds to nutrient enrichment there is no published literature relating it to N deposition. It does not occur on the most acid soils (Grime *et al,* 2007) so may not be suitable as an indicator of acid deposition.
- ***Bellis perennis*** – *B. perennis* is a very widespread species typical of amenity grasslands. It has an intermediate Ellenberg score (Hill *et al,* 1999) and rarely occurs

on soils with a pH below 5.5 (Grime *et al,* 2007). This means it is unlikely to be suitable as an indicator of N deposition.

- ***Carduus nutans*** – This species has a moderately low Ellenberg score (Hill *et al,* 1999) and is mainly found on chalk, limestone or lime-enriched soils (Preston *et al,* 2002) meaning it is unlikely to be a good indicator of eutrophication or acidification.
- ***Cerastium fontanum*** – Although *C. fontanum* is usually found in fertile habitats (Preston *et al,* 2002) it is infrequent below a soil pH of 4.5 (Grime *et al,* 2007) meaning it is unlikely to be a good indicator of acid deposition.
- ***Chamerion angustifolium*** – This species is a colonist of disturbed and burnt ground (Preston *et al,* 2002). It has a moderately low Ellenberg score (Hill *et al,* 1999) so is unlikely to be a good negative site condition indicator of N deposition.
- ***Cirsium arvense*** - *C. arvense* is a species of richly fertile habitats (Hill *et al,* 1999). There is currently no evidence to suggest that it increases at high N deposition.
- ***Cirsium vulgare***- *C. vulgare* is also a species of richly fertile habitats (Hill *et al,* 1999). As with *C. arvense*, there is currently no evidence to suggest that it increases at high N deposition.
- ***Dactylis glomerata*** – This species is generally found in fertile habitats (Hill *et al,* 1999; Sinker *et al,* 1985) on neutral or basic soils. It occurs less frequently on acid soils (Grime *et al,* 2007) so it unlikely to be a good indicator of acid deposition.
- ***Deschampsia flexuosa*** – *D. flexuosa* is a species of moderately nutrient poor habitats and acid soils (Hill *et al,* 1999; Sinker *et al,* 1985). Evidence from woodlands (Nordin *et al,* 2006; Pitcairn *et al,* 1998) and heathlands (Alonso *et al,* 2001; Hartley and Mitchell, 2005) have shown increases in *D. flexuosa* with increasing N inputs but there is no evidence to show if this is the case in grasslands. However, long term N addition experiments in Surrey and Cheshire found no increase in this species except in combination with disturbance (cutting – causing opening of the heather canopy) at the northern experimental site. Further research would be needed to establish whether this species was an indicator in grasslands.
- ***Holcus lanatus*** – In woodlands *H. lanatus* has been shown to occur more frequently close to point sources of ammonia (Pitcairn *et al,* 1998) but as with *D. flexuosa* the is no evidence of response in grasslands. Despite frequently occurring in a survey of acid grasslands in relation to N deposition there was no evidence to indicate increases in *H. lanatus* (Stevens *et al,* 2004).
- ***Lolium perenne*** – This is a species typical of improved grasslands. Although it is found in very fertile conditions and is certainly an indicator of nutrient rich habitats there is no evidence relating it to N deposition.
- ***Phleum pratense*** – As with *L. perenne*, *P. pratense* is a species typical of fertile habitats (Hill *et al,* 1999) but there is no evidence linking it to N deposition. This means it is difficult to separate effects of fertilisation from the impacts of N deposition.
- ***Plantago major*** – *P. major* is a species of richly fertile habitats (Hill *et al,* 1999) but is more typically characterised by its presence in areas of heavy trampling. There is no evidence to suggest it increases with N deposition.
- ***Senecio jacobaea*** – This species is typical of overgrazed grasslands. It is a species of intermediate fertility (Hill *et al,* 1999). There is no evidence to suggest it increases with N deposition.
- ***Trifolium repens*** – *T. repens* is another species of fertile habitats (Hill *et al,* 1999) but again there is no evidence to suggest it increases with N deposition making it hard to separate impacts from other causes of nutrient enrichment.

- ***Urtica dioica*** – *U. dioica* is a species of very fertile habitats (Hill *et al,* 1999) and has been shown to occur more frequently close to point sources of ammonia (Pitcairn *et al,* 1998). There is no evidence of increases in acid grasslands that can be related to N deposition.

4.1.3 Additional indicators covered for upland acid grassland (JNCC, 2006) - Negative site condition indicators

- ***Ranunculus repens*** – *R. repens* is a species of richly fertile habitats (Hill *et al,* 1999). It is generally absent from soils with a pH below 4.5 (Grime *et al,* 2007) so it unlikely to be a good indicator of acid deposition.
- ***Cynosurus cristatus*** – *C. cristatus* has a wide tolerance of nutrient levels and is found in both nutrient-poor and -rich habitats (Sinker *et al,* 1985). As with *R. repens*, it is generally absent from very acid soils (Grime *et al,* 2007) meaning it unlikely to be a good indicator of acid deposition.
- **Large *Rumex* spp.** – The large *Rumex* species are all found in richly fertile habitats (Hill *et al,* 1999). Although they indicate nutrient enrichment, there is no evidence linking them directly to N deposition. Thus it would be difficult to attribute changes to N deposition rather than other sources of enrichment.
- ***Juncus effusus*** – This species is typical of wet acid grasslands. It has an intermediate Ellenberg value (Hill *et al,* 1999). There is no evidence linking increases in this species to N deposition.
- ***Juncus squarrosus*** – This species is typical of very unproductive and infertile habitats (Hill *et al,* 1999; Grime *et al,* 2007). It is favoured by heavy grazing and trampling. It is unlikely to respond positively to N deposition.
- ***Rhytidiadelphus squarrosus*** – Long-term additions of N to acid grasslands have resulted in declines in *R. squarrosus* stem density at highest treatment levels (Carroll *et al,* 2000). Despite frequently occurring in a survey of acid grasslands in relation to N deposition there was no evidence to indicate increases in the cover of this moss (Stevens *et al,* 2004) suggesting that it is not suitable as a negative site condition indicator.

4.1.4 Additional indicators covered for upland acid grassland (JNCC, 2006) - Potential site condition indicators for acid grasslands

Potential site condition indicators for acid grasslands are: *Calluna vulgaris* (+), *Campanula rotundifolia* (+), *Galium verum* (+), *Lotus corniculatus* (+) and *Deschapsia flexuosa* (-). There is no conclusive evidence for any of these species and further research is needed to determine their value as indicators.

4.2 Bogs

4.2.1 Upland blanket bog and valley mires (JNCC, 2006) - Positive site condition indicators

- ***Andromeda polifolia*** – This species is found in extremely infertile habitats (Hill *et al,* 1999). Long-term experimental additions of 30 kg N ha^{-1} yr^{-1} resulted in an increase in *A. polifolia* cover (Wiedermann *et al,* 2007) suggesting it is not suitable as a positive site condition indicator species for N deposition.

- ***Arctostaphylos* spp.** – This species has a restricted distribution, it is only found in low N deposition areas in the UK making it difficult to assess its value as an indicator for N deposition.
- ***Betula nana*** – This species has a restricted distribution, it is only found in low N deposition areas in the UK making it difficult to assess its value as an indicator of N deposition. Additionally no significant effects of nitrogen addition were found after three years of treatment in *B. nana* tundra communities in Norway (Paal *et al,* 1997)
- ***Carex bigelowii*** – *C. bigelowii* has a low Ellenberg value (Hill *et al,* 1999) but Pearce and van der Wal (2002) found increases in cover with low level N applications in *Racomitrium* heath. This would indicate that it is not a suitable positive site condition indicator species for N deposition.
- ***Calluna vulgaris*** - *C. vulgaris* is described above for grasslands. This is a potential indicator of N deposition in a competitive situation.
- ***Cornus suecica*** – This species has a low Ellenberg value (Hill *et al,* 1999) but there is no evidence of responses to N deposition.
- ***Drosera* spp.** – *Drosera* spp. are all indicators of very low nutrient status. An N addition experiment has shown populations decreased within two years of N addition and then remained low (Redbotorstensson, 1994). This group is a potential positive site condition indicator for N deposition.
- ***Erica* spp.** - *E. cinerea* and *E. tetralix* are described above for grasslands. As a group the species differ in their response to nutrient enrichment so are not suitable as an indicator.
- ***Empetrum nigrum*** – Although *E. nigrum* has a very low Ellenberg value (Hill *et al,* 1999) investigations in Norway suggested this species is increased in vigour by N deposition (Tybirk *et al,* 2000). This means it is probably not suitable as an indicator of N deposition.
- ***Eriophorum angustifolium*** – *E. angustifolium* also has a very low Ellenberg value (Hill *et al,* 1999) but studies in Holland have suggested that its growth is not limited by N (Heijmans *et al,* 2002) so this species is not a suitable indicator of N deposition.
- ***Eriophorum vaginatum*** – This species has shown increases in cover with N additions over three years (Redbotorstensson, 1994). Long-term experimental additions of 30 kg N ha^{-1} yr^{-1} also resulted in an increase in cover (Wiedermann *et al,* 2007) and increase in biomass was found with wet and dry deposition in a controlled experiment (Leith *et al,* 2001). These results suggest that it is not suitable as a positive site condition indicator for N deposition.
- ***Menyanthes trifoliata*** – Sinker *et al* (1985) describe this species as occurring at nutrient levels from low to rich. In a Russian experiment small doses of N and P or N and K fertilisers resulted in increased cover (Maksimova and Yudina, 1999) suggesting it is not suitable as a positive site condition indicator.
- ***Myrica gale*** – *M. gale* is a species of low nutrient habitats (Hill *et al,* 1999) but there is no evidence to link it to N deposition.
- ***Narthecium ossifragum*** – This species is found in very low nutrient environments (Hill *et al,* 1999) but is also described as indicative of areas on a bog where there is some flushing or water movement to replenish the nutrient supply (Sinker *et al,* 1985). Leith *et al* (2001) found *N. ossifragum* significantly increased in biomass with nitrate addition. Spink and Parsons (1995) investigated the impacts of N deposition on *N. ossifragum* and concluded that even in relatively unpolluted conditions N deposition was too high for *N. ossifragum*. However, 20 years after Spink and Parsons transplanted this species into a bog surface in the South Pennines this species

is growing well. These contradictory results mean this species would need further investigation before it could be used as an indicator of N deposition.

- **Non-crustose lichens** – some species of lichen are more sensitive to N deposition than others and factors such as climate, substrate and vascular species cover may be more important in determining the distribution of some lichen species (Fremstad *et al,* 2005). Effects of N deposition have been observed on lichen communities (e.g. Power *et al,* 2006) and some species may be suitable for monitoring N deposition (Frati *et al,* 2007). See earlier note about *Cladonia* spp.
- **Pleurocarpous mosses** – Pleurocarpous mosses cover a wide range of species with different nutrient requirements. As a group the responses of individual species are too diverse for them to be a suitable indicator of N deposition although individual species may be. The same is true for liverworts.
- ***Racomitrium lanuginosum*** – There have been no investigations of this species in bogs but in *Racomitrium* heath low level N additions (10 kg N ha^{-1} yr^{-1}) have shown *R. lanuginosum* cover reduced and growth severely inhibited (Pearce and van der Wal, 2002; Pearce *et al,* 2003). This species is potentially an indicator of N deposition (Pearce and van der Wal, in press).
- ***Rubus chamaemorus*** – This species is found in very low nutrient environments (Hill *et al,* 1999) but there is no evidence relating it to N deposition.
- ***Rhynchospora alba*** – N applications to a *Sphagnum* bog community in the Netherlands favoured *R. alba* and resulted in this becoming the dominant species (Heijmans *et al,* 2002). This suggests it is not suitable as a positive site condition indicator for N deposition.
- ***Sphagnum* spp.** – Although some *Sphagnum* species respond negatively to N deposition (e.g. *S. magellanicum* (Limpens and Berendse, 2003)) this is not the case for all species (e.g. *S. fallax* (Limpens *et al,* 2003)) so as a group *Sphagnum* is not a suitable indicator of N deposition although individual species may be. The recovery, evident but slow, of *Sphagnum* communities on the South Pennine blanket bogs despite the continuing high nitrogen deposition indicates that certain species are relatively nitrogen tolerant (e.g. *S. cuspidatum, S. fallax*) but others are still rare and probably nitrogen-affected, particularly the important hummock types *S. papillosum* and *S. capillifolium* (Lee, 1998; Caporn *et al*, 2006). The more minerotrophic conditions of the valley bogs should mean these are less influenced by acid and nitrogen deposition in comparison with the ombrotrophic bog surfaces, but nitrogen deposition will most likely lead to increased graminoid competition (Hall *et al,* 2003).
- ***Sphagnum fallax*** – Investigations in the Netherlands have indicated that *S. fallax* responds positively to N deposition (Limpens *et al,* 2003) so it is unlikely to be a good positive indicator of N deposition.
- ***Trichophorum cespitosum*** – *T. cespitosum* is a species of low nutrient habitats (Hill *et al,* 1999) but there is no evidence to link it to N deposition.
- ***Vaccinium* spp.** – *Vaccinium* spp. vary in their nutrient requirements and tolerances (Hill *et al,* 1999; Sinker *et al,* 1985) so as a group are not suitable as an indicator of N deposition.

4.2.2 Upland blanket bog and valley mires (JNCC, 2006) - Negative site condition indicators

- ***Agrostis capillaris*** – *A. capillaris* is a species of habitats with intermediate fertility (Hill *et al,* 1999). Investigations into the effects of wet and dry N deposition on *A.*

capillaris showed negative impacts at even low levels of N deposition (Kupcinskiene *et al,* 1997).
- ***Holcus lanatus*** - In woodlands *H. lanatus* has been shown to occur more frequently close to point sources of ammonia (Pitcairn *et al,* 1998) but there is no evidence of response in bogs.
- ***Phragmites australis*** – *P. australis* is an indicator of fertile habitats (Hill *et al,* 1999; Sinker *et al,* 1985) but is not found in acid habitats (Sinker *et al,* 1985) so is unlikely to be a good indicator of N deposition.
- ***Pteridium aquilinum*** – *P. aquilinum* is a species of moderately infertile habitats (Hill *et al,* 1999). In heathland N addition has been shown to have only short-lived benefits to *P. aquilinum* growth (Gordon *et al,* 1999) suggesting that it would not be a good indicator of N deposition.
- ***Ranunculus repens*** – This species is found in richly fertile habitats but is only found in moderately acid environments. As a result of this it is unlikely to be suitable as an indicator of N deposition.

4.2.3 Additional indicators for Lowland raised bogs and blanket bogs (JNCC, 2004b) - Positive site condition indicators

- **Drosera rotundifolia** – see Drosera spp. above
- **Erica tetralix** – see above for acid grasslands.
- **Sphagnum capillifolium** – experimental N applications have shown a reduction in shoot branching on *S.* capillifolium under highest treatments (Carfrae *et al,* 2007) however, the treatment levels were 64kg N ha^{-1} yr^{-1}, levels much higher than we would expect in the UK. New research from the long-term (started 2002) N addition experiment at Whim bog, Midlothian (Sheppard & Leith unpublished presentation, November 2007) has demonstrated that of the three main species at this site, *S.* capillifolium was most negatively affected, even at additions of 8 kg N ha^{-1} y^{-1}.
- **Sphagnum cuspidatum** – transplant experiments using *S.* cuspidatum from both clean and polluted sites in the UK suggests intra-specific differences in the moss from the two locations (Baxter *et al,* 1992). This would suggest that is may not be suitable as an indicator of N deposition. It is also reasonably abundant in the South Pennines (Caporn *et al,* 2006)
- **Sphagnum magellanicum** – Very high levels of N deposition have shown reductions in *S.* magellanicum growth (80 kg N ha^{-1} yr^{-1}) but lower levels did not show the same result (Limpens and Berendse, 2003). In a separate experiment additions of 50 kg N ha^{-1} yr^{-1} did not show any reductions in growth after 3 years (Heijmans *et al,* 2002). These levels are still much higher than those found in the UK.
- **Sphagnum papillosum** – This species has shown increased growth with increasing N deposition up to 30kg N ha^{-1} yr^{-1} with experimental N application in the Netherlands (van der Heijden *et al,* 2000). This would suggest that it is not suitable as a positive site condition indicator for N deposition.
- **Sphagnum pulchrum** – There is no evidence in the literature linking this species to N deposition.
- **Sphagnum tenellum** - There is no evidence in the literature linking this species to N deposition.
- **Vaccinium oxycoccus** – V. oxycoccus has shown increased biomass with N additions of up to 50 kg N ha^{-1} yr^{-1} (Heijmans *et al,* 2002) suggesting it is not suitable as a positive site condition indicator for N deposition.

4.2.4 Additional indicators for Lowland raised bogs and blanket bogs (JNCC, 2004b) - Negative site condition indicators

- ***Cirsium* spp.** – *Cirsium* spp. have mixed nutrient requirements so as a genus are not suitable as an indicator of N deposition.
- ***Deschampsia cespitosa*** – This species has been shown to increase in cover in response to experimental N addition in the absence of grazing but not where grazing was present (Alonso *et al,* 2001). This interaction means it is probably not a suitable indicator as many bogs are grazed at low intensities.
- ***Epilobium hirsutum*** – Although an indicator of high nutrient status (Hill *et al,* 1999), *E. hirsutum* is not found on acid soils (Preston *et al,* 2002) so it unlikely to be a good indicator of acidification from N deposition.
- ***Glyceria maxima*** – Although an indicator of high nutrient status (Hill *et al,* 1999), there is no evidence in the literature linking this species to N deposition.
- ***Phalaris arundinacea***– *P. arundinacea* is a species of richly fertile habitats (Hill *et al,* 1999) but it is not found on soils with a pH of below approximately 5 (Sinker *et al,* 1985; Grime *et al,* 2007). Laboratory experiments showed that this species is not promoted by aerial deposition of ammonia (Adrizal *et al,* 2006).
- ***Polytrichium* spp.** - There is no evidence in the literature linking this species to N deposition and, despite frequently occurring in a survey of acid grasslands in relation to N deposition, there was no evidence to indicate that this species responded to N deposition (Stevens *et al,* 2004).
- ***Rubus fruticosus*** – This species aggregate contains 386 microspecies which differ in the soil nutrient and pH requirements (Grime *et al,* 2007). This means it is unlikely to be a good indicator of N deposition.
- ***Urtica dioica*** – *U. dioica* is a species of very fertile habitats (Hill *et al,* 1999). Hogg *et al* (1995) described increases in the cover of *U. dioica* in a valley mire which they attributed to heavy atmospheric N deposition. This species is a potential indicator of N deposition in bogs where other sources of eutrophication can be ruled out.

Potential indicators for bogs are: *Calluna vulgaris* (+), *Drosera* spp. (+), *Racomitrium lanuginosum* (+), *Sphagnum capillifolium* (+) and *Urtica dioica* (-). As with grasslands there is no conclusive evidence for any of these species and further research is needed to determine their value as indicators.

4.3 Heathland

4.3.1 Sub-alpine dry dwarf-shrub heath (JNCC, 2004a) - Positive site condition indictors

- ***Arctostaphylos* spp.** – These are species typical of nutrient poor heaths, but have a restricted northern distribution making it difficult to assess its value as an indicator for N deposition.
- ***Betula nana*** - *B. nana has a* very restricted north of Scotland distribution (Preston *et al,* 2002) making it unsuitable as an indicator of N deposition.
- ***Calluna vulgaris*** – (See note for grasslands). In upland dry heath nitrogen accelerates the growth rate and stage of development (Carroll *et al,* 1999). Nitrogen can therefore bring forward the mature or degenerate phase when other species could invade. But

this will depend on the intensity and frequency of management and the current growth stage (Calvo *et al,* 2007). So it is probably an unreliable indicator on managed heaths.

- ***Erica* spp.** – This group is not specific enough to be an indicator as different *Erica* species have different niche requirements.
- ***Empetrum nigrum*** – abundant in the southern Pennines bogs and heaths where N deposition is high, so an unlikely indicator of N deposition.
- ***Racomitrium lanuginosum*** - on *Racomitrium* heaths in Scotland there is good evidence of sensitivity to nitrogen; impacts may be more directly related to concentration of nitrogen solutes rather than dose (Pearce and van der Wal, 2008).
- ***Genista anglica*** - Around the UK this species has a rather scattered distribution in low nutrient conditions, found in lowlands on relatively humid grass heaths and around the drier fringes of bogs; in upland areas it occurs in healthy, damp, unimproved pastures (Preston *et al,* 2002). It is vulnerable to grass competitors if grazing is reduced but there is no information on N sensitivity.
- ***Myrica gale*** – This species has mainly a restricted western distribution in Britain in low nutrient conditions but there is no information on N sensitivity.
- ***Salix repens*** – *S. repens* has variable habitats in different nutrient conditions depending on whether it is the erect or prostrate variety (Preston *et al,* 2002) making it unsuitable as an indicator.
- ***Ulex gallii*** - Mainly found in western England and Wales, so not widespread in the UK. There is no knowledge of N sensitivity for this species.
- ***Vaccinium spp.*** - This group is too general for use as an N deposition indicator (but see notes below on lowland dry heath).

4.3.2 Sub-alpine dry dwarf-shrub heath (JNCC, 2004a) - Negative site condition indicators

- ***Campylopus spp.*** – Although negative indicators in the sense that they can form thick carpets suppressing other species, these moss are often simply a feature of an early successional stage rather than an indicator of N deposition.
- ***Cirsium arvense*** – *C. arvense* is a weed of fertile habitats and not likely to be N sensitive.
- ***Cirsium vulgare*** – As *C. arvense* (above).
- ***Juncus effusus*** – This is a species of generally nutrient poor wet pastures, but there is no evidence that it is affected by N deposition.
- ***Polytrichum spp.*** – As several species exist this is too general for an N deposition indicator.
- ***Pteridium aquilinum*** - An increasing species but in upland dry heath limited by low temperatures. There is no clear evidence that it is responsive in the field to nitrogen deposition.
- ***Rumex* spp. (large spp. not including *R. acetosa*)** – this grouping is too general to be of use as an indicator of N deposition although the species are all typical of nutrient rich habitats.
- ***Ranunculus repens*** - *R. repens* is a species of richly fertile habitats (Hill *et al,* 1999). It is generally absent from soils with a pH below 4.5 (Grime *et al,* 2007) so it unlikely to be a good indicator of acid deposition.
- ***Urtica dioica*** - a species of very fertile habitats (Hill *et al,* 1999); its presence in heathlands is more likely to indicate disturbance or localised eutrophication rather than N deposition.

4.3.3 Additional indicators for Wet heath – lowland (JNCC, 2004c) - Positive site condition indicators

- ***Anagallis tenella*** – This species is found on a variety of wet heath sites and requires open patches so it is vulnerable to competition if the site subject to N deposition but there is no information on N sensitivity.
- ***Carex panicea*** – *C. panicea* occurs in wide range of habitats where competitors are suppressed by nutrient poor or grazed conditions (Grime *et al,* 2007). It is in decline due to habitat loss but its response to N in heathlands is not known.
- ***Carex pulicaris*** - *This species* favours slightly minerotrophic soil conditions of varied pH so is unlikely to be N sensitive.
- ***Drosera* spp.** - *Drosera* spp. are all indicators of very low nutrient status. An N addition experiment has shown populations decreased within two years of N addition and then remained low (Redbotorstensson, 1994). This group is a potential positive indicator of N deposition. *Drosera rotundifolia* is the most useful because of its wider distribution.
- ***Eleocharis* spp.** – There are several different species of *Eleocharis* which grow in a range of nutrient conditions, so unlikely to be N deposition sensitive.
- ***Erica ciliaris*** - This species has a very restricted south-west distribution so is not suitable as an indicator of N deposition.
- ***Erica cinerea*** - This species occupies the drier sites on acidic soils usually accompanied by *Calluna vulgaris*. Growth in experiments was increased by N (Caporn, unpublished) but its sensitivity in the field is unknown.
- ***Erica tetralix*** - (see note for aid grassland) Recent experiments on Whim lowland bog showed strong positive responses to ammonium-N additions (Sheppard & Leith, unpublished) so it is not likely to be a good N indicator for positive site condition.
- ***Erica vagans*** - This species has a very restricted local occurrence so is not suitable as an indicator of N deposition.
- ***Eriophorum angustifolium*** – see note for bogs
- ***Galium saxatile*** - *A*n indicator of unimproved acid grassland (Preston *et al,* 2002) but not found to be related to N deposition in grasslands (Stevens *et al,* 2004). There is no further evidence from heathlands.
- ***Genista anglica*** - The direct effects of N unknown, but this species is vulnerable to competition in agriculturally 'improved' areas (Preston *et al,* 2002). Further research is needed to determine if this species would be suitable as an indicator of N deposition.
- ***Juncus acutiflorus*** – The sensitivity of this species to N deposition is not known.
- ***Juncus articulatus*** – *J. articulatus* occupies a wide range of wet habitats and is unlikely to be nutrient sensitive.
- ***Narthecium ossifragum*** - (see note for bogs) Unlikely to be a reliable N deposition indicator.
- ***Pinguicula* spp.** – these insectivorous plants indicate low N conditions, the most widespread is *P. vulgaris*, but all are found in nutrient poor conditions. There is no evidence of there response to N deposition but these may be potential indicators of N deposition with further research.
- ***Polygala serpyllifolia*** –This species is declining in southern England, but N sensitivity unknown.

- ***Potentilla erecta*** - This species is found is too greater range of nutrient status to be an indicator of N deposition in heathlands.
- ***Rhynchospora alba*** – This species might increase at expense of bryophytes (see note for bogs) but further research would be needed to determine if it is an indicator of N.
- ***Schoenus nigricans*** - This species is found on base rich substrates so would not be a good indicator of acidification.
- ***Serratula tinctoria*** - This is a species of nutrient poor habitats (Hill *et al,* 1999; Sinker *et al,* 1985) but there is no evidence of it responding to N deposition or fertiliser addition.
- ***Succisa pratensis*** – *S. pratensis* is found in free draining, mildly acidic soils; there is no knowledge of N sensitivity.
- ***Trichophorum cespitosum*** – There is no evidence relating this species to N deposition in heathlands.
- ***Ulex minor*** - This species has a restricted south-west distribution so is not suitable as an indicator of N deposition.

4.3.4 Additional indicators for Wet heath – lowland (JNCC, 2004c) -Negative site condition indicators

- **Acrocarpous mosses** - This group is too general to be useful as indicators of N because different species show different responses.
- ***Alnus glutinosa*** **–** This species is a nitrogen fixing tree, its presence more likely to indicate lack of site management.
- ***Apium nodiflorum*** – *A. nodiflorum* is characteristic of nutrient enriched sites (Preston *et al,* 2002), so could be of value if other sources of nitrogen could be excluded
- ***Betula*** **spp.** - This group is too general to be useful as indicators of N because different species show different responses.
- ***Digitalis purpurea*** – This species would tend to indicate disturbance rather than nutrient enrichment.
- ***Epilobium*** **spp. (excl.** ***E. palustre*****)** - This group is too general for use as an indicator of N deposition, but some *Epilobium* species are indicators of disturbance and other local enrichment.
- ***Fallopia japonica*** - This species is a fast growing competitive weed, and is unlikely to be a good indicator of N deposition.
- ***Gaultheria shallon*** – This species is ericaceous so is unlikely to be N sensitive.
- ***Glyceria fluitans*** – This is a marshland species, tolerant of high levels of disturbance and nutrient-enrichment, it could be an N indicator if other sources of enrichment are accounted for but further research would be needed to determine this.
- ***Juncus squarrosus*** – This species is typical of very unproductive and infertile habitats (Hill *et al,* 1999; Grime *et al,* 2007). It is favoured by heavy grazing and trampling but did not increase in Ruabon long term N experiment (Caporn, unpublished).
- ***Molinia caerulea*** – This species should be no more than occasional in heathland as it may indicate eutrophication; however management, particularly burning, and climate influences are also important. In the Netherlands experiments have shown the high potential growth rate of *Molinia* allows it to out-compete other species (including *Calluna* and *Erica* sp.) at high N (Aerts *et al,* 1990). This is a potential negative indicator of N deposition although further research would be needed at the lower deposition rates found in the UK.

- ***Oenanthe crocata*** – *O. crocata* occupies a variety of shallow water/marshland sites (Preston *et al,* 2002) and is probably insensitive to a range of nutrient conditions.
- ***Phragmites spp.*** – Phragmites species would tend to be found in more enriched conditions (see *P. australis* below).
- ***Pinus* spp.** - This group is too general to be useful as indicators of N because different species show different responses.
- ***Prunus spinosa*** - *P. spinosa* is a species of intermediate nutrient conditions (Hill *et al,* 1999) but there is no evidence linking it to N deposition.
- ***Quercus* spp.** - This group is too general to be useful as indicators of N because different species show different responses.
- ***Ranunculus repens*** – *R. repens* is a species of intermédiate nutrient conditions (Hill *et al,* 1999) but there is no evidence linking it to N deposition in heathlands.
- ***Rhododendron ponticum*** – *Rhododendron* is ericaceous so likely to be N sensitive. It is also likely to be managed to curb invasion making it unsuitable as an indicator of N enrichment.
- ***Rubus* spp.** - This group is too general to be useful as indicators of N because different species show different responses although some species in this group tend to be indicators of nutrient enrichment.
- ***Rumex obtusifolius*** - This species is typical of very fertile habitats (Hill *et al,* 1999); its presence in heathlands is more likely to indicate localised eutrophication rather than N deposition.
- ***Salix* spp.** - This group is too general to be useful as indicators of N because different species show different responses.
- ***Senecio jacobaea*** - There is no evidence to link prevalence of *S. jacobea* with N deposition.
- ***Typha* spp.** – This wetland species likely to indicate mesotrophic and eutrophic conditions but there is no specific evidence linking it to N deposition in heathlands.
- ***Ulex europaeus*** - This species has low nutrient requirements and is unlikely to be a negative site condition indicator for N deposition.

4.3.5 Additional indicators for Wet heath – upland (JNCC, 2004a) - Positive site condition indicators

- ***Andromeda polifolia*** - A species of infertile habitats (Hill *et al,* 1999) and restricted to a central UK distribution. Long-term experimental additions of 30 kg N ha^{-1} yr^{-1} resulted in an increase in *A. polifolia* cover (Wiedermann *et al,* 2007) suggesting it is not suitable as a positive site condition indicator species for N deposition.
- ***Arctostaphylos uva-ursi*** - This species has a restricted distribution, it is only found in low N deposition areas in the UK making it difficult to assess its value as an indicator for N deposition.
- ***Carex spp.*** – Too variable as a group to be of value as an indicator.
- ***Empetrum nigrum*** – This species is abundant in the southern Pennines bogs and heaths where deposition is high, so is an unlikely indicator for N deposition.
- Non-crustose lichens - (See earlier note for bogs) the fruticose *Cladonia* lichens were sensitive to nitrogen on upland heath at Ruabon (Pilkington *et al,* 2007) and *Cladonia portentosa* is a good candidate as an indicator of low nitrogen conditions on upland heaths.
- **Pleurocarpous mosses** - As a group these are too varied in habitat preference and Ellenberg rank to be of use as indicators of N deposition.

- ***Rubus chamaemorus*** – This species is restricted to a northern distribution. It is fairly common in the polluted southern Pennines, and not clearly related to nitrogen deposition.
- ***Sphagnum spp.*** - This genus include a well recognized range of species occupying a spectrum of nutrient and hydrology conditions. As a group they are not a useful diagnostic tool, but individual species can be.

4.3.6 Additional indicators for Wet heath – upland (JNCC, 2004a) - Negative site condition indicators

- ***Agrostis capillaris*** – *A. capillaris* occupies a very wide range of habitats and nutrient conditions so is not a good indicator of nitrogen.
- ***Holcus lanatus*** – As with *A. capillaris*, *H. lanatus* is found in a wide range of nutrient conditions and habitats so is not suitable as an indicator.
- ***Phragmites australis*** - Locally known to increase due to eutrophication related to a multitude of causes (Preston *et al,* 2002). This species could be a nitrogen deposition indicator if other sources of enrichment (such as groundwater) could be excluded.

4.3.7 Additional indicators for Lowland dry heath (JNCC, 2004c) - Positive site condition indicators

- ***Armeria maritima*** – Mainly restricted to coastal areas, but otherwise inland very locally distributed e.g. mine waste sites making it unsuitable as an indicator of N deposition.
- ***Ammophila arenaria*** – This species is rare away from the coast; it is likely to be nutrient sensitive but there is no information on this.
- ***Genista pilosa*** – This species is restricted to south west Britain so is not suitable as an indicator.
- ***Hypochaeris radicata*** – *H. radicata* enjoys a wide range of habitats particularly on slightly acidic, sandy soil, it is not favoured by nutrient enrichment (Grime *et al,* 2007), but its response to N addition is unknown.
- ***Lotus corniculatus*** - A species of low nutrient soils. Stevens *et al* (2004) identified this as a species that showed declines along the UK gradient of N deposition. This would suggest that it may be suitable as an indicator of N deposition in heathlands but further research would be needed to confirm this.
- ***Plantago lanceolata*** – A very successful plant on moderate to low fertility soils; its occupancy of a wide habitat range makes it unlikely as an indicator of N deposition.
- ***Plantago maritima*** - This species is restricted to coastal or saline-affected regions so is unsuitable as an indicator of N deposition.
- ***Rumex acetosella*** - A weedy species of low nutrient soils that quickly occupies newly open spaces. Opportunistic nature unlikely to make it a good N indicator.
- ***Scilla verna*** - The restricted north and western distribution of this species means it is not suitable as an indicator of N deposition.
- ***Thymus praecox*** - A species of low nutrient soils but having a variable response to N additions in grassland experiments.
- ***Vaccinium myrtillus*** – In heathlands *V. myrtillus* often accompanies *Calluna vulgaris*. Cover of *V. myrtillus* was not affected by high nitrogen treatments at Ruabon upland heath (Carroll *et al,* 1999), so an unlikely indicator in heaths of N deposition.

- ***Vaccinium vitis-idaea*** (and hybrids) – This species tends to grow better when supplied with nitrogen (Caporn, unpublished), but it is also restricted mainly to north and westerly regions of the UK (Preston *et al,* 2002) meaning it is not suitable as an indicator of N deposition.
- ***Viola riviniana*** - This species is found on wide ranging soil types making this an unlikely N indicator species.

4.3.8 For limestone heath only:

- ***Filipendula vulgaris*** – This species is found mainly on base rich substrates so is unlikely to be an indicator of acid deposition.
- ***Galium verum*** – *G. verum* occupies a wide range of habitats (Preston *et al,* 2002) but vulnerable to competition from vigorous grasses. There is no clear evidence in heathlands if it is a potential N indicator.
- ***Helianthemum nummularium*** - This is mainly a species of calcareous soils, on heaths more likely to be influenced by base status (Preston *et al,* 2002) than N deposition.
- ***Sanguisorba minor*** – As with *H. nummularium* this species is more likely to be influenced by base status of the soil than N deposition.

4.3.9 For dune heath only:

- ***Aira praecox*** – There *is* no evidence of a direct response to N, but may be crowded out by tall competitors in N enriched conditions (see note for acid grassland). Further investigation would be needed before recommending this as an indicator species.
- ***Corynephorus canescens*** - This species has a restricted distribution making it difficult to assess its value as an indicator for N deposition.
- ***Phleum arenarium*** - *P. arenarium* is widely distributed in dune heath and there is no indication of a decline; there is also no knowledge of an N response.
- ***Erodium cicutarium*** – *E. cicutarium* is found at intermediate nutrient levels (Hill *et al,* 1999), and is an unlikely N indicator.
- ***Filago minima*** – This species is an annual of dry, open, infertile, acidic to neutral soils in a wide range of habitats; it is in decline across the UK (Preston *et al,* 2002) so may be responsive to nitrogen but there is no evidence for this.
- ***Sedum acre*** - A species of shallow, infertile soils and bare rock, sensitivity to N is likely, but there is no information available on this.
- ***Peltigera spp.*** – A lichen genus of that is typical of low nutrient conditions. This genus could be N indicators in dune heaths but there is no information available on their N response.

4.3.10 Negative site condition indicators

- ***Agrostis* spp.** - This group is too general to be useful as indicators of N because different species show different responses.
- ***Chamerion angustifolium*** - a known competitive species of disturbed and burnt ground (Preston *et al,* 2002) this is more likely to determine its distribution than N deposition.

- ***Danthonia decumbens*** - A grass species of mildly acidic or calcareous soils, excluded from fertile grassland (Grime *et al,* 1988). There is no information on N sensitivity for this species.
- ***Festuca* spp.** - This group is too general to be useful as indicators of N because different species show different responses.
- ***Hippophae rhamnoides*** - This species is mainly coastal but planted widely inland, so not a good indicator.
- ***Nardus stricta*** - *N. stricta* has been shown to increase with N deposition in heathlands in combination with grazing (although not when grazers were excluded (Alonso *et al,* 2001; Hartley and Mitchell, 2005). High levels of ammonium nitrate supplied as a mist increased the biomass of *N. stricta* in a laboratory study (Leith *et al,* 1999). This species is a potential indicator of N deposition in grazed heathland.
- ***Ranunculus* spp.** - This group is too general to be useful as indicators of N because different species show different responses.
- ***Senecio* spp.** - This group is too general to be useful as indicators of N because different species show different responses.
- ***Sarothamnus scoparius*** – This species is widely planted so not a good indicator.

Potential indicators for heathlands are: *Racomitrium languinosum* (+), *Drosera* spp. (+), *Molinea caerulea* (-) and *Nardus stricta* (-). As with other habitats, there is no conclusive evidence for any of these species and further research is needed to determine their value as indicators of N deposition and whether impacts can be separated from management effects.

4.4 Woodland

The CSM guidance for woodlands does not identify any positive or negative site condition indicator species. There are a number of woodland habitats specified in the guidance for bryophytes and lichens (JNCC, 2005). These will be evaluated for their value as indicators of N deposition.

4.4.1 Positive site condition indicators

- **Caliciales** – Although several species are known to avoid urban areas there has been no research that we can identify separating the effects of different forms of acid deposition for this species.
- ***Bryoria* spp.** – *Bryoria fuscesens* was among species identified as more tolerant to higher nitrogen levels in a survey of Atlantic oak woods (Mitchell *et al,* 2005) suggesting that the family as a whole does not make a suitable indicator.
- ***Alectoria sarmentosa sarmentosa*** – The species is identified by the United States Forest Service as a species especially sensitive to nitrogen and sulphur pollution (Geiser *et al,* 1994) but there is no evidence that makes it possible to examine these pollutants separately.
- ***Lobaria* spp.** – Although sensitive to air pollution there is no evidence specifically linking this family of lichens to N deposition.
- ***Usnea* spp.** – As with *Bryoria* spp (above), at least one species in this family, *Usnea subfloridana*, is thought to be associated with high levels of N deposition (Mitchell *et al,* 2005).
- ***Parmelietum laevigatae*** – There is no evidence linking this species association with nitrogen deposition.

4.4.2 Negative site condition indicators

- **Pleurocarpous mosses** – This group is too broad to be useful as an indicator of N deposition as it contains species that are likely to be sensitive to N deposition as well as those that are more tolerant.
- **Green algae** – although associated with air pollution there is not enough evidence to separate the effect of nitrogen pollution from other atmospheric pollutants.

There are no potential indicators of N deposition within existing woodland guidance.

4.5 Ellenberg values

Although Ellenberg values provide a useful tool for identifying species characteristic of fertile habitats, Ellenberg values alone are not sufficient evidence of a reaction to N deposition. Indeed, a large change in Ellenberg value in a habitat is unlikely to be as a result of N deposition but more likely to be as a result of eutrophication from another source. Many species respond to eutrophication but few of these species can be specifically related to N deposition. Further research is needed for the majority of species to relate responses to eutrophication to N deposition. There is a lack of information for many of the species investigated here and further information is needed to determine if they are likely to be good indicators.

5 What additional indicator species could be added to CSM guidance to help detect and attribute air pollution impacts?

We have taken two different approaches for identifying additional indicator species. The first approach was to use canonical correspondence analysis to identify species correlated with high or low levels of N deposition. We have also used data from long term experiments and monitoring combined with surveys and review of literature to explore potential indicators.

5.1 Canonical correspondence analysis

Canonical correspondence analysis (CCA) is a multivariate ordination technique for direct gradient analysis. Species composition is directly related to measured environmental variables (Palmer, 2002). It assumes species have unimodal distributions along environmental gradients. The resultant ordination diagram conveys large amounts of information regarding the environmental variables and their relations to species. CCA distributes individual species in the ordination diagram in a position that reflects their net tolerance to the environmental factors based on their cover and frequency. CCA was carried out using CANOCO 4.5 (ter Braak and Smilauer, 2002).

Species data were entered as percentage cover or domin scores. The N deposition estimates were extracted from 5km by 5km maps for the UK and comprise measured wet deposition including orographic enhancement, and dry deposition of NH_3, NO_2 and HNO_3 from measured concentration fields and a dry deposition model (Smith *et al,* 2000; NEGTAP, 2001).

5.2 Acid grassland indicators

In order to identify potential positive and negative site condition indicators of N deposition in acid grassland we used three different data sets. The data were analysed independently because different collection methods meant that they were not directly comparable. The results of the different surveys are compared in order to identify robust indicators.

The first data used were a survey of 68 U4 grassland sites. These data were collected during 2002 and 2003 as part of the project 'Ecosystem properties of acid grassland along a gradient of N deposition' (Stevens, 2004; Stevens *et al,* 2004; Stevens *et al,* 2006). This data set encompasses both upland and lowland U4 grasslands throughout England, Scotland and Wales. Five randomly placed 2x2m quadrats were taken at each of the 68 sites. The data used in the analysis are mean percentage cover from each species. Modelled N deposition data provided by CEH Edinburgh for the period 1998 and 2000 was used (Smith *et al,* 2000). N deposition ranged from 6 to 36 kg N ha^{-1} yr^{-1}. Species that occurred in less than 10% of the sites were removed so that they did not skew the distribution. Rare species would also not be suitable as indicators.

Several species were either positively or negatively correlated with N deposition in this analysis; outliers with particularly strong positive or negative correlations have been selected as potential indicators (Figure 5.1). Positive correlations (i.e. negative site condition indicators) were found with *Hypnum cupressiforme*, and *Carex panicea*. Negative correlations (i.e. positive site condition indicators) were found with *Plantago lanceolata*, *Calluna vulgaris*, *Euphrasia officinalis*, *Lotus corniculatus*, *Campanula rotundifolia* and *Hylocomium splendens*. Figure 1 shows the ordination diagram for this data set.

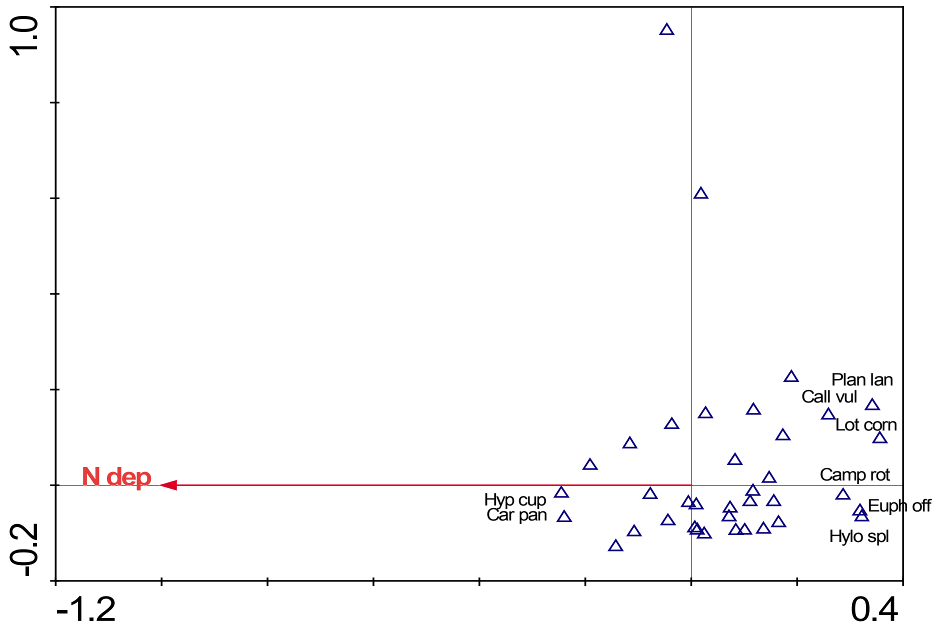

Figure 5.1. CCA ordination showing species that were positively and negatively correlated with N deposition in the Stevens (2004) data set.

The second data set used was restricted to lowland acid grasslands in Wales covering the communities U1, U2, U3 and U4 (CCW, 2004). Most of the data were from U4 grasslands. 905 2x2m quadrats collected between 1988 and 2004 were included in the analysis. These were placed in homogeneous stands of vegetation. Species cover was recorded using the Domin scale. Some locations have more than one quadrat recorded in a relevant vegetation type. Because there were varying numbers of replicates these were treated as separate samples. Modelled deposition was not available for the whole range of years for which vegetation data were available, so modelled N deposition for the period 1995 and 1997 was used. This is toward the middle of the data set and represents years when much of data were collected. N deposition ranged from 7 to 28 kg N ha^{-1} yr^{-1}. Species that occurred in less than 10% of the sites were removed.

In this data set, negative correlations with N deposition (positive site condition) were found for *Veronica chamaedrys* and *Ranunculus bulbosus*. Positive correlations with N deposition were found for *Rumex acetosella*, *Hypnum cupressiforme*, *Calluna vulgaris* and *Carex panicea*. However, these data are tightly clustered on the N deposition axis and none of the species are clear indicators. The ordination is shown in Figure 5.2.

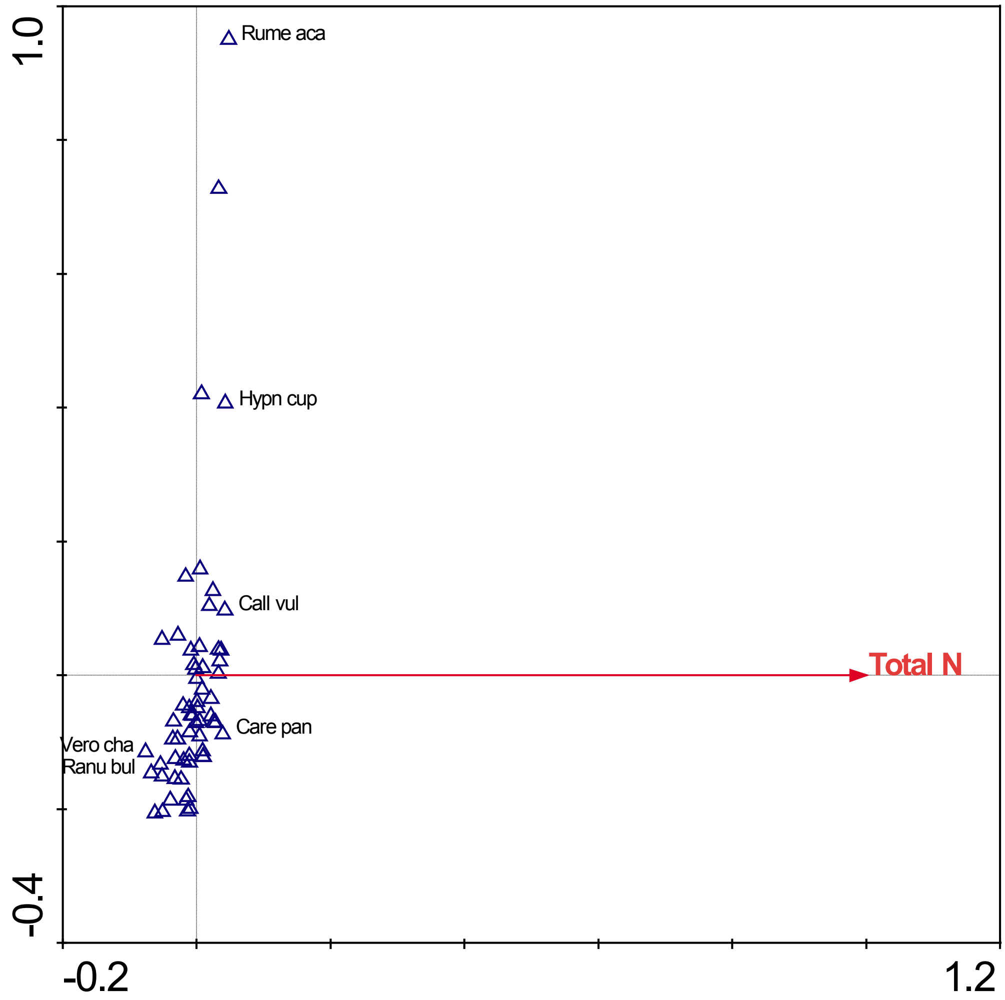

Figure 5.2. CCA ordination showing species that were positively and negatively correlated with N deposition in the CCW (2004) data set.

The third data set was taken from the Countryside Survey of Great Britain (Smart *et al,* 2003). This is a nationwide survey of 1km squares based on a stratified random sampling system where the stratification is by landclass (these are a combination of soils, geology, OS data, climate). Within the 1km squares, all of the habitats are mapped and a number of different plot types are sampled. Some of these are randomly placed nested plots (X plots), for this analysis the inner nest was used; some are stratified random located in particular habitat types (U plots) and some are targeted on semi-natural habitat patches missed by the other plots in each square. They are all 2m x 2m in size. For this analysis, only plots from 1998 were used. They were all allocated to an NVC community. To select acid grassland, firstly plots were selected by broad habitat type as identified by the land-cover mapping carried out in each square, then within this a subset was selected which were classified to an acid grassland NVC category with a Jaccard coefficient of greater than 0.5.

Figure 5.3 shows a CCA ordination of species in the countryside survey data. The considerable variation in this data set compared to the last two is shown in the scale of the x axis.

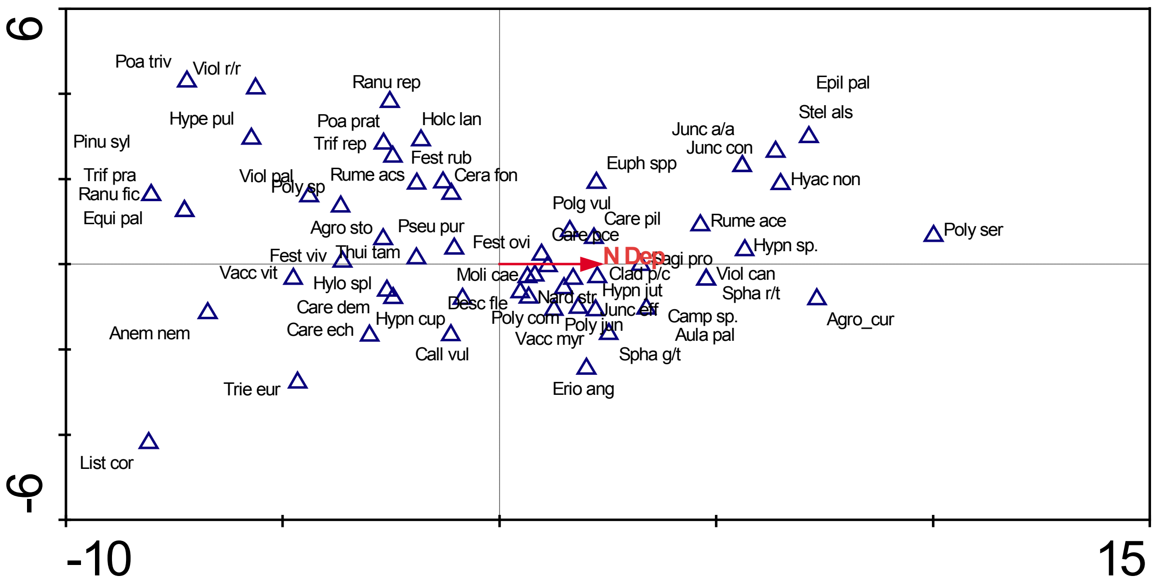

Figure 5.3. CCA ordination showing acid grassland species in the countryside survey (Smart *et al,* 2003) data set.

Comparing the different data sets will allow us to identify the most robust indicators across the different grassland communities. The strongest positive site condition indicator identified from the Stevens data set was *Lotus corniculatus*. However, closer examination of these data reveals that this relationship is driven primarily by a single outlier. When this is removed, there is no significant relationship. *Campanula rotundifolia* and *Euphrasia officinalis* are both close to the centre of the ordination in the CCW data. In the countryside survey ordination they fall on the low N deposition side of the ordination. *C. rotundifolia* is a species of infertile habitats (Preston *et al,* 2002; Hill *et al,* 1999) and is described as intolerant of competition with vigorous grasses (Sinker *et al,* 1985). There is no experimental evidence linking this species with N deposition. *E. officinalis* is actually an aggregate of a number of micro-species that were not differentiated in any of the studies considered due to their difficult taxonomy. This species is a small hemi-parasitic annual on the roots of herbs and small shrubs (Preston *et al,* 2002), and hence a decline in the host plants might be an explanation for the decline of *E. officinalis*. It is very difficult to determine if its decline is a direct response or a response to the decline in host species.

Plantago lanceolata and *Hylocomium splendens* are also close to the centre of both the CCW and countryside survey ordinations but show slight positive correlations in the CCW data, which would suggest they are not as suitable as indicators. *Calluna vulgaris* is close to the centre of the countryside survey ordination but shows a positive association with N deposition in the Welsh data set. All of these species occurred at all levels of deposition in the Stevens data but their change in abundance led to the negative correlation with N deposition. N addition experiments have identified a reduction in *C. vulgaris* cover as a result of competition with grasses (e.g. Heil and Diemont, 1983), increased frost sensitivity

(Caporn *et al,* 2000), winter desiccation (Sheppard and Leith, 2002) and increased susceptibility to heather beetle (*Lochmaea suturalis*) attack (Brunsting and Heil, 1985) but *Calluna* has also been shown to respond positively to N addition with increased growth (e.g. Carfrae *et al,* 2004; Carroll *et al,* 1999 and see section 5.4). Two positive site condition indicators were identified in the CCW data although the ordination shows there is little difference between species related to N deposition (they are clustered close together (Figure 5.2). *V. chamaedrys* has an intermediate Ellenberg N and *R. bulbosus* has a low Ellenberg score (Hill *et al,* 1999) but there is no experimental evidence linking either species to N deposition.

Negative indicators of site condition (high N deposition) from the Stevens data were *Hypnum cupressiforme*, and *Carex panicea*. Both of these species were found as negative site condition indicators in the CCW data but *C. panicea* showed a slight negative association in the countryside survey. There is no experimental evidence relating this species to N deposition although sedges in general have been shown to increase in some habitats (e.g. van der Wal., 2003) and this is not a species we would expect to respond positively. *H. cupressiforme* was close to the centre of the countryside survey ordination although here more species were differentiated and *H. jutlandicum* showed a positive association as did *Hypnum* sp. *H. cupressiforme* is a pollution-tolerant moss (Rodenkirchen, 1992), and has been found to persist in areas where other bryophytes have declined considerably due to N deposition (Hallingback, 1992). *H. jutlandicum* has been shown to increase in cover with the addition of 20 kg N ha^{-1} yr^{-1} (B. J. Haworth, pers. comm.) in heathlands and has shown a positive response to N addition in high Arctic heath (Gordon *et al,* 2001). This pollution tolerance would allow *H. cupressiforme* to compete well with more sensitive mosses. The final indicator for negative condition in the CCW data was *C. vulgaris,* which is discussed above. All three of these species occurred at all levels of deposition in all of the data sets, but increased in their occurrence and cover at higher levels of deposition where they were positively correlated.

Although the data from the different surveys appear at times to be contradictory, there are a number of potential reasons for this. The first is that the three data sets cover different regions and ranges of N deposition. This means care must be taken in interpreting the data, maximum deposition in the CCW data is not as high as the Stevens data meaning particular care should be taken in interpreting negative site condition indicators. The three ordinations also cover different grassland types.

Given the findings above, there are a number of species that could potentially be added to CSM guidance as positive or negative site condition indicators of N deposition in acid grasslands:

Table 5.1. Positive site condition indicator species in acid grasslands (upland and lowland) for atmospheric N deposition and supporting evidence. Ticks for each survey indicate a consistent Message.

Species	Ellenberg score	Supporting evidence	CCW	CS	Stevens	Ease of identi-fication	Suitability as indicator
Ranunculus bulbosus	Moderate (4)	-	✓	-	-	Easy with guidance	Poor – insufficient evidence
Veronica chamaedrys	Moderate (5)	-	✓	-	-	Easy	Poor – insufficient evidence
Plantago lanceolata	Moderate (4)	Yes	X	✓	✓	Easy	Poor – mixed evidence
Calluna vulgaris	Low (2)	Mixed	X	✓	✓	Easy	Poor – mixed evidence
Euphrasia officinalis	Low (3)	-	✓	✓	✓	Aggregate is easy	Poor, occurs across range
Campanula rotundifolia	Low (2)	-	✓	✓	✓	Easy	Poor, occurs across range
Hylocomium splendens	Low (2)	Yes	X	✓	✓	Easy with guidance	Poor – mixed evidence

Table 5.2. Negative site condition indicator species in acid grasslands (upland and lowland) for atmospheric N deposition and supporting evidence. Ticks for each survey indicate a consistent Message.

Species	Ellenberg score	Supporting evidence	CCW	CS	Stevens	Ease of identi-fication	Suitability as indicator
Hypnum cupressiforme	Moderate (4)	Yes	✓	✓	✓	Easy with guidance	Poor, occurs across range
Carex panicea	Low (2)	-	✓	✓	✓	Easy with guidance	Poor, occurs across range
Calluna vulgaris	Low (2)	Mixed	X	✓	✓	Easy	Poor – mixed evidence

These results suggest that presence or absence of species alone is not sufficient to determine the impacts of N deposition. There are no species that are sufficiently restricted in their distribution by N deposition in acid grasslands that they make suitable indicators.

5.3 Bog indicators

The countryside survey data set was used to look for positive and negative site condition indicators of N deposition in bogs. Similar to the approach used above by identifying those that were located in mapped polygons assigned to the Bog broad habitat and then matching an NVC bog community (M1-M4, M6, M15-M21, M25, H9, H12 (bog on deep peat)) with a

Jaccard coefficient of >0.5. As above the plots were 2m x 2m in size X, Y, U plots (Smart *et al*, 2003). Figure 5.4 shows a CCA ordination with N deposition as constraining variable of species in the countryside survey data.

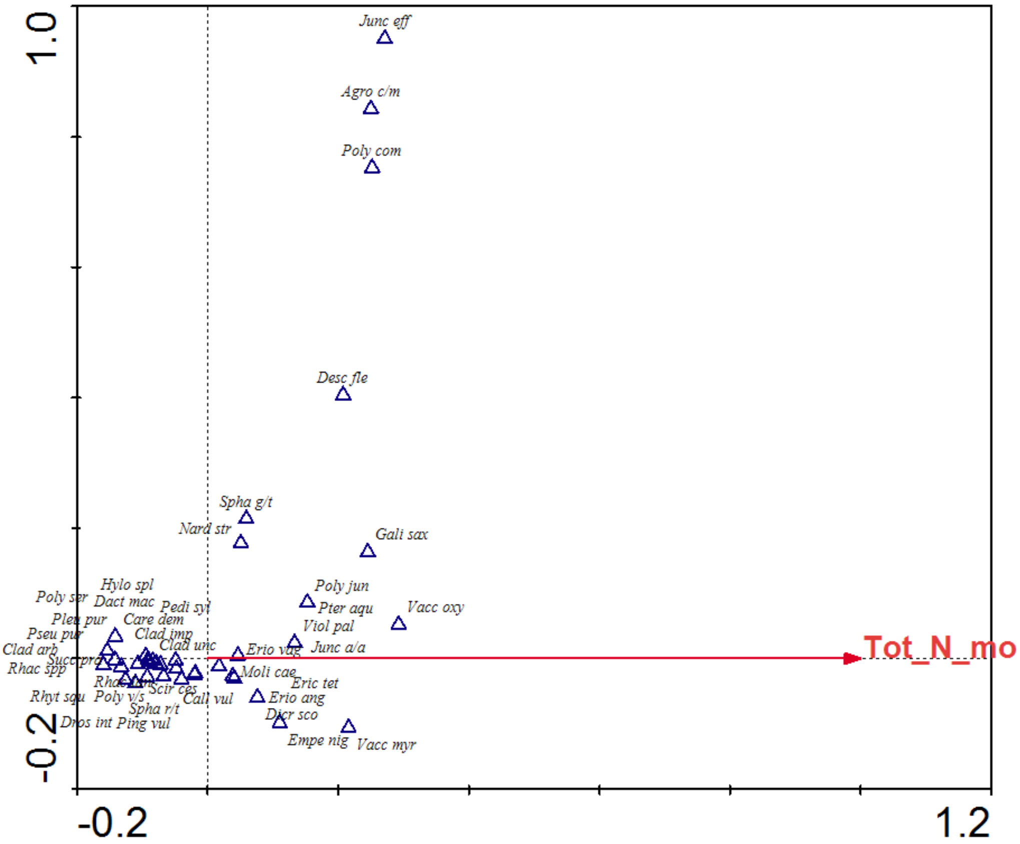

Figure 5.4. CCA ordination showing bog species in the countryside survey (Smart *et al,* 2003) data set.

Species positively associated with N in this data set were the dwarf shrubs *Vaccinium oxycoccus*, *Vaccinium myrtillus* and *Empetrum nigrum*, the grasses *Agrostis canina* sens lat and *Deschampsia flexuosa*, the bryophyte *Polytrichum commune*, and the forb *Galium saxatile* and rush *Juncus effusus.*

Negative site condition indicators for N include the lichen *Cladonia arbuscula,* the bryophytes *Pleurozia purpurea, Hylocomium splendens* and *Rhytidiadelphus squarrosus,* and the small forbs *Drosera intermedia, Pinguicula vulgaris, Polygala serpyllifolia, Succisa pratensis, Pedicularis sylvatica* and *Dactylorhiza maculata.*

The literature suggests certain species that might be affected by N in bogs. *Molinia caerulea* has been shown to increase in ombrotrophic *Molinia-Sphagnum* bog (Limpens *et al,* 2003, Tomassen *et al,* 2003, 2004). However, in the countryside survey data it was in the centre of the ordination, showing only a slight positive response to N. *Deschampsia flexuosa* has also been shown to increase (Aaby, 1994).

Sphagnum species e.g. *S. cuspidatum, S. magellanicum, S. fallax, S. palustre* and *S. fimbriatum* have all been shown to decrease with N addition (Hogg *et al,* 1995, Lutke Twenhoven, 1992, Nordin and Gunnarsson., 2000, Lee *et al,* 1998a, Press *et al,* 1988). In one study as *S. fallax* decreased *Polytrichum strictum* increased in cover (Mitchell, 2002). In countryside survey data *Polytrichum commune* showed a positive response to N deposition.

In the countryside survey because of difficulties in identification *Sphagnum* species have been amalgamated into categories, *Sphagnum* red/thin, *Sphagnum* red/fat, *Sphagnum* green/thin, *Sphagnum* green/fat. This ensures that *Sphagnum* is recorded and some additional information about the type of *Sphagnum* collected. The categorisation is shown in Table 5.3. However, these *Sphagnum* categories did not respond significantly to N in the countryside survey data. Red/thin *Sphagnum* (e.g. *Sphagnum capillifolium* and *S. russowi*) showed a slight negative response to N, however, red fat *Sphagnum* (*S. magellanicum, S. subnitens*), green thin *Sphagnum* (e.g. *S. fimbriatum*, *S. recurvum* and *S. fuscum*) and green fat *Sphagnum* (e.g. *S. palustre, S. papillosum and S. compactum*) all showed a positive response to N deposition.

Table 5.3. Categorisation of mosses in the countryside survey.

Green/Fat	**Green/Thin**	**Red/Fat**	**Red/Thin**
S. compactum	sect. Cuspidata*	*S. magellanicum*	*S. capillifolium*
S. molle	*S. fimbriatum*	*S. subnitens*	*S. russowii* (red form)
S. palustre	*S. fuscum*		*S. warnstorfii*
S. papillosum	*S. girgensohnii*		
S. squarrosum	*S. recurvum*		
S. strictum	*S. russowii* (green form)		
S. subsecundum (Sect.)	*S. quinquefarium*		
S. teres	(* includes *S. recurvum* and *S. cuspidatum*)		

Small species such as *Drosera rotundifolia* have been shown to decline in response to increased growth of competitive species such as *Eriophorum* and *Vaccinium vitis-idea* (Redbo-Torstensson, 1994), *D. rotundifolia* showed a slight negative relationship with N in the countryside survey data whilst both *Eriophorum* and *Vaccinium* showed a positive response.

An increased growth of trees (particularly *Pinus sylvestris*) has been shown for many ombrotrophic sites in Sweden (Gunnarson *et al,* 2002).

Recent observations of bryophytes on the southern Pennine blanket bogs are of interest since this area has been affected by air pollution since at least the Industrial revolution owing to its downwind proximity to the Manchester-Liverpool and Potteries conurbations. Surveys at three permanent sites in the southern Pennines in 2005-6 repeated earlier studies as part of a PhD by Colin Studholme in the 1980s. There was a large increase in total bryophytes species (see section 6) over a time when N deposition has been consistently high (in excess of 30 kg ha^{-1} y^{-1}). The improvement is most likely to be a response to reduction in sulphur pollution (although grazing intensity has also fallen dramatically in the recent decade). The most common species at both these sites in the 1980s and in 2005-6, *S. cuspidatum* was found in more pools and in larger amounts at the later date than twenty years earlier. *S. fallax* was also common. There was also a large increase in the total number of *Sphagnum* species observed at both sites in comparison with those in 1983-85. *S. subnitens* and *S. fimbriatum* species were also observed forming hummocks around the pools. Away from the pools occasional hummocks were evident comprising *S. subnitens* and, less commonly, *S. palustre* and *S. papillosum*. Recently a small amount of *S. capillifolium* was recorded at Holme Moss.

Other non-*Sphagnum* moss species also showed substantial increases between 1983-5 and 2005-6. At both sites the moss *Warnstorfia fluitans* (formerly known as *Drepanocladus fluitans),* growing on the edges or within the pools was observed in the 1980s and in 2005-6. Very little else was found in the 1980s (Table 5.4). However, by 2005-6 there was a very wide range of moss species, with most visible being the dark green cushions of *Campylopus flexuosus*. The increase in liverworts was more striking as there were no records from the open plots in 1983-5, but several species found in 2005-6. Similar recording effort and skills in identification were used in both surveys.

Table 5.4. Moss species other than *Sphagnum* found in ombrotrophic, un-marked plots at two sites in the Dark Peak SSSI in the period 1983-4 reported by Studholme (1989) and in 2005-6 (from Caporn *et al,* 2006).

	1983-4		2005-6	
	Holme Moss	Alport Moor	Holme Moss	Alport Moor
Mosses				
Brachythecium rutabulum			●	●
Campylopus flexuosus			●	●
Campylopus introflexus	●		●	●
Campylopus pyriformis			●	
Ceratodon purpureus			●	
Dicranella heteromalla				●
Dicranum polysetum				●
Dicranum scoparium				●
Kindbergia praelonga				●
Hypnum cupressiforme		●		
Hypnum jutlandicum			●	
Hypnum lacunosum				●
Orthodontium lineare			●	
Plagiothecium denticulatum				●
Plagiothecium undulatum			●	
Pohlia nutans				●
Polytrichum commune			●	
Rhytidadelphus squarrosus				●
Splachnum sphaericum	●			
Warnstorfia fluitans	●	●	●	●
Liverworts				
Calypogia azurea			●	
Calypogia muelleriana			●	●
Cephalozia bicuspidata			●	●
Diplophyllum albicans			●	
Gymnocolea inflata			●	●
Lophocolea bidentata				●
Lophozia ventricosa				●

N and sulphur deposition have both fallen since the 1980s but the southern Pennines still receives as much N deposition as anywhere in the UK (Fowler *et al,* 2005). Therefore, the observations of increases in *Sphagnum* and other bryophytes are difficult to interpret. However, the most common species of *Sphagnum* (*S. cuspidatum* and *S. fallax*) both now and in the 1980s cannot be viewed as potential indicators of clean conditions. Others that have increased such as *S. palustre, S. fimbriatum* and *S. subnitens* are also likely to be fairly pollution tolerant (and are known to have a more minerotrophic preference), while those that are only very slowly appearing – *S. capillifolium* and *S. papillosum* - are the more sensitive, truly ombrotrophic *Sphagnum* species.

Table 5.5. Negative site condition indicator species in bogs (blanket and raised in uplands and lowland) for atmospheric N deposition and supporting evidence. Ticks for each survey indicate a consistent message.

Species	Ellenberg score	Reference	CS	Ease of identification	Suitability as indicator
Vaccinium myrtillus	Low (2)		✓	Easy	Possible to relate increase to N dep (but is quite common in Bog environment)
Agrostis canina	Med (3)		✓	Moderate	
Deschampsia flexuosa	Med (3)	Aaby 1990, 1994	✓	Easy	Possible to relate increase to N dep (but is quite common in Bog environment)
Polytrichum commune	Low (2)		✓	Easy	Possibly if *Sphagnum* decreases and *Polytrichum* increases
Galium saxatile	Med (3)		✓	Easy	Poor - common in Bog environment
Juncus effusus	Med (4)		✓	Easy	Poor - common in Bog environment
Molinia caerulea	Low (2)	Limpens *et al,* 2003, Tomassen *et al,* 2003, 2004	X	Easy	Possible-can relate increase to N dep (but is quite common in Bog environment and can be due to poor management)

Table 5.6. Positive site condition indicator species in bogs (blanket and raised in uplands and lowland) for atmospheric N deposition and supporting evidence. Ticks for each survey indicate a consistent Message.

Species	Ellenberg score	Reference	CS	Ease of identification	Suitability as indicator
Rhytidiadelphus squarrosus	High (4)		✓	Easy	Poor- too ubiquitous
Pleurozia purpurea	Low (1)		✓	Difficult	Poor because of ID problems
Hylocomium splendens	Low (2)		✓	Easy	Good
Drosera intermedia	Low (1)		✓	Easy	Good
Pinguicula vulgaris	Low (2)		✓	Easy	Good
Polygala serpyllifolia	Low (2)		✓	Easy	Good
Pedicularis sylvatica	Low (2)		✓	Easy	Good
Dactylorhiza maculata	Low (2)		✓	Easy	Good
Sphagnum species e.g. *S. magellanicum, S. fallax, S. cuspidatum*	Low (1-3)	Hogg *et al,* 1995, Lutke Twenhoven, 1992, Nordin and Gunnarsson, 2000, Press *et al,* 1988	X	Difficult to species level but can use categorisation	Good- although mixed evidence from CS and southern Pennines.
Drosera rotundifolia	Low (1)	Redbo-Torstensson, 1994	✓	Easy	Good

As with heathlands, in bogs it is very often the response to N of competitive species and interactions with grazing that influences the species composition rather than direct effects of N (van der Wal *et al,* 2003). Many of the suggested indicators have relatively low Ellenberg N scores but often only a slight change is sufficient to alter community dynamics.

It should be possible to use some of the species as indicators. Species likely to increase with N and so indicate poor condition include *Vaccinium myrtillus, Deschampsia flexuosa* and *Molinia caerulea*. It should be emphasised that their presence is not a negative indication, it is when they increase at the expense of other species. The increase of moss species other than *Sphagnum* such as *Polytrichum commune* might be of some use but relies on good identification skills.

Positive indicators of site condition i.e. those likely to be present at low levels and indicating a site is in good condition include *Sphagnum* species, *Hylocomium splendens* and smaller forbs such as *Drosera rotundifolia, D. intermedia, Pinguicula vulgaris, Polygala serpyllifolia, Dactylorhiza maculata and Pedicularis sylvatica.*

5.4 Dwarf shrub heath indicators

To identify potential species indicators of N deposition we have focussed on upland and lowland dry heath. These have been studied in depth through long term N addition experiments since 1989 on an upland heather moor (NVC H12) near Ruabon in north Wales (e.g. Carroll *et al,* 1999, Pilkington *et al,* 2007) and since 1996 at a lowland dry heath (NVC H9) near Little Budworth in Cheshire (Wilson, 2003; Caporn 2007). In the case of the upland dry heath these studies were supported by field surveys of vegetation and plant-soil biogeochemistry along gradients of N pollution in north-west Britain in 2005 and 2006 (Edmondson, 2007; Caporn *et al,* 2007).

5.4.1 Experimental nitrogen addition to upland dry heath at Ruabon

Experimental design. The original experiment started in 1989 and vegetation plots (1 x 1 m) (called the old plots), in a randomised block design, received monthly additions of ammonium nitrate solutions which provided 0, 40, 80, 120 kg N ha^{-1} y^{-1}. In 2000, after eleven years of treatment the experimental plots and surrounding land were given a controlled burn as part of the normal moorland management. Re-growth since the burn has been followed. In 1998 a further set of larger plots (2 x 2 m) (called the new plots) were set up and these incorporated a wider range of treatments to better cover the lower range of N loads: 0, 10, 20, 40, 120 kg N ha^{-1} y^{-1}. Phosphorus treatments were also introduced at some of the N loadings in order to investigate how this nutrient affected the response to N. In 2003 a recovery experiment was initiated by halting N additions to half of each plot, but continuing additions to the other side. Ruabon moor has a history of management by controlled burning.

Results:

Higher plant responses

The vegetation at the Ruabon experiment comprises dominant *Calluna vulgaris* and a subordinate understorey of *Vaccinium myrtillus*. The other occasional species are *Deschampsia flexuosa* and *Juncus squarrosus* while other higher plants such as *Galium saxatile*, *Festuca rubra* and *Potentilla erecta* are rare within the heather dominated stands although they are present at small amounts in the area as a whole.

In both the old and new plot experiments, the N treatments accelerated growth and the phases of development of *Calluna*, in comparison with the control plots, and increased the occurrence of gaps in the canopy as the stands aged prior to the burn. However, throughout both experiments, *Calluna* has remained the dominant higher plant and no consistent changes in the other vascular plant species have been observed. The absence of invasion by grass at the higher rates of N input, a feature expected on the basis of Dutch experiments (e.g. Hiel & Diemont, 1978), might be explained by the lack of grass propagules locally or the presence of a dense moss cover, excluding grass invaders, or other factors.

While the experiments at Ruabon have not generated any plant species indicators of eutrophication, the failure of grasses (e.g. *Deschampsia flexuosa*) or other herbaceous vegetation to establish in N-treated plots (up to 120 kg N ha^{-1} y^{-1} for as long as 19 years) - suggests that the absence of such invaders cannot be seen as a sign that the habitat is *not* nutrient enriched. This type of moorland is typically managed to maximise the period when a

Calluna canopy is dominant and minimise the phase when other vascular plants might establish.

Bryophytes and Lichens

Within a few years of the start of the original Ruabon experiment it was clear that while the abundance of vascular plants was relatively insensitive to N, the lichen and bryophyte flora in general were negatively affected by N additions (assessed using pin quadrat monitoring; Carroll *et al,* 1999). As a group, lichens appeared most sensitive, responding adversely in the new plot experiment to additions of just 10 kg N ha^{-1} y^{-1} (Pilkington *et al,* 2007). *Cladonia* species were the most abundant lichens and *C. portentosa* is potentially a negative site condition indicator for N pollution, owing particularly to its relative ease of identification and supporting knowledge of its response to N deposition (Hyvarinen and Crittenden, 1998).

The effects of N additions on bryophyte species were assessed in 2005 on the new plots at Ruabon after 7 years of treatment (Edmondson, 2007). The abundance of species on the plots was assessed by measurements of cover and frequency within quadrat frames sub-divisions. The responses (Table 3.7) indicate changes in either or both cover and frequency. In several cases obvious reductions in bryophytes, shown as a (–) mark in Table 3.5, were not statistically significant owing to high variability in the data and the small number (n=4) of replicate plots.

The plot survey found that N significantly reduced both the total bryophyte and total moss abundance. For individual moss species, four showed a clear reduction in cover and frequency with N addition, these were: *H. jutlandicum, R. squarrosus, P. nutans* and *C. flexuosus* and in the latter these changes were statistically significant. Liverworts were less abundant than mosses at Ruabon and three species showed clear reductions in cover and frequency, these were *Lophocolea bidentata, Calypogeia muelleriana and Lophozia ventricosa*, and again in the latter this effect was statistically significant. The other bryophytes in the new plots at Ruabon showed no obvious trend in response to N. The declining bryophyte species on average had a lower Ellenberg (N) score (2.1) than those that did not show any change (3.1). The clearest decline of any bryophyte was *Campylopus flexuosus* with an Ellenberg (N) of one.

Table 5.7. Bryophytes in the Ruabon new plots, 2005 (adapted from Edmondson, 2007).

Group / species	N effect	Stat. significance	Ellenberg No.
All Bryophytes	-	<0.05	
All Mosses	-	<0.05	
Hypnum jutlandicum	-	ns	2
Pohlia nutans	-	ns	2
Rhytidiadelphus squarrosus	-	ns	4
Campylopus flexuosus	-	<0.001	1
Dicranum scoparium	0	ns	2
Eurhynchium praelongum	0	ns	5
Pleurozium schreberi	0	ns	2
Plagiothecium undulatum	0	ns	2
Pseudoscleropodium purum	0	ns	3
Brachythecium rutabulum	0	ns	6
All Liverworts	-	ns	
Lophocolea bidentata	-	ns	3
Calypogeia muelleriana	-	ns	1
Lophozia ventricosa	-	<0.05	2
Lepidozia reptans	0	ns	2

Foot note: An effect of N marked as (-) indicates a dose-related reduction in frequency and/or cover with increasing N treatments. The sign (0) indicates no clear change in abundance.

Approximately 2¼ years following halting of N addition to half of each plot the recovery of bryophytes was assessed as part of the above survey. The liverworts in general showed a positive, significant recovery, particularly at the lower range of treatments, while the abundance of mosses and overall bryophytes did not change. There was no significant recovery in any individual bryophyte species although a positive trend was exhibited in some of the N sensitive species (e.g. *Campylopus flexuosus, Lophozia ventricosa).* Further monitoring of recovery in this experiment is planned and is expected to reveal further change.

The same survey in 2005 examined the combined N x phosphorus treatment plots and these showed very positive bryophyte responses to increased phosphate supply at all levels of N addition. Furthermore the phosphorus treatment alleviated the negative effect of N in both mosses and liverworts. These data are not presented here but suggest that phosphorus status of a habitat could strongly alter the value of bryophytes as indicators of N pollution.

Additional bryophyte survey data at Ruabon

Further knowledge of species responses to N at Ruabon was provided by Haworth's study of the old plots 2 years after the burn (Ashmore *et al,* 2004). The monitoring was at an earlier successional stage following fire when the *Calluna* canopy was more open and bryophytes were mainly acrocarpous rather than pleurocarpous – in contrast to the later stage studied by Edmondson (2007). The study of Haworth found that *Campylopus* species were by far the dominant bryophytes and their abundance were increased by moderate N additions. Two other mosses, *Pohlia nutans* and *Hypnum jutlandicum* were negatively affected by N while the other pleurocarpous species showed no obvious response to the N additions. Haworth found only small amounts of liverworts and lichens at this stage of stand development, and the *Cladonia* spp. tended to be negatively impacted.

In summary, the study of bryophyte and lichen species at Ruabon by Edmondson and Haworth demonstrated that overall the bryophytes and lichens were negatively impacted by N; some species were strongly inhibited while others were less affected. Certain sensitive species might therefore be candidates as negative site condition indicators for N pollution (Table 1) but there were no consistent positive indicators of N enrichment. There was a transient increase in some *Campylopus* species (*including C. flexuosus)* after the fire, but these acrocarpous forms decline as the canopy develops over them. This investigation therefore highlights the crucial influence of timing of monitoring during the *Calluna* stand's cyclical development and the potential influence of other nutrient limitations – such as phosphorus availability.

Further observations of the effects of N additions on bryophytes were made at Budworth Common by Wilson (2003), Haworth (in Ashmore, 2004) and Ray, (2007). All researchers found that *Hypnum jutlandicum* was dominant while other bryophytes and lichens appeared rarely. An N treatment of 20 kg ha^{-1} y^{-1} above the ambient (approximately 20 kg ha^{-1} y^{-1}) was optimal for the abundance of this moss, but higher loadings reduced its cover. Several observations at Budworth (and Ruabon) indicated that the *Hypnum jutlandicum* cover response to N was influenced by N both directly and indirectly via changes in the light penetrating through the *Calluna* canopy as treatments accelerated heather growth.

5.4.2 Vegetation change along nitrogen pollution gradients in north-west Britain

Complementing the bryophyte species monitoring on the N experimental plots at Ruabon in 2005, regional surveys on comparable heather moorland sites covering parts of northern England, Wales and Scotland were performed by Edmondson in 2005 and Carroll and Caporn in 2006 (Edmondson, 2007; Caporn *et al,* 2007). In view of the important influence of stand development highlighted in the plot study, care was taken to ensure that regional survey plots were at a comparable stage of development. Five (0.5 x 0.5 m) quadrats were sampled at each site and species presence scored. Frequency of presence in the 5 quadrats was the measure of relative abundance. The target species of the vegetation were bryophytes but other plants were recorded also. Soil and plant nutrient measurements were made in each quadrat.

This regional survey work detected variations in bryophyte and higher plant species richness with the greatest in Scotland and the poorest in the southern Pennines and these differences correlate with the gradient of N pollution (see Question 4).

Excluding rarities and very local species, a few bryophytes from the data set were examined as potential indicator of N pollution. These were the following mosses (with Ellenberg N ranking in brackets): *Hylocomium splendens* (2) and *Dicranum scoparium* (2) which were expected to decline with increasing N deposition on the basis of other research (*H. splendens*) (see references below) and monitoring at Ruabon (*D. scoparium*). Two moss species, *Eurhynchium praelongum* (5) and *Hypnum jutlandicum* (2), which might be expected to increase on the basis of Ellenberg N score (*E. praelongum*) and observations at the Budworth N experiment (see above) were also investigated from the survey data.

Of these four moss species, the only one showing consistent difference between low and high N sites was *Hylocomium splendens*. The relationship between *H. splendens* and N deposition was quantified by analysing the frequency at each of the survey sites over the combined 2005-6 data sets (Figure 5.5). This moss was very common in the Cairngorms, infrequent at the locations studied in north Wales and absent from southern Pennine sites. At the Welsh and Pennines sites it was generally replaced as the dominant bryophyte by *Hypnum jutlandicum*. The contrasting abundance of *Hylocomium splendens* between Scottish and South Pennines sites deserves further investigation but does not reflect climate as it is recorded nationally in the south as well as the north (Smith, 2003) although management may be a contributing factor. When frequency is plotted against modelled annual average NO_2 concentration, the relationship with pollution is sharper still and a threshold is suggested at approximately 10-15 µg m^{-3} above which it may not be found (Figure 5.6), a value considerably below the ecosystem Critical Level of 30 µg m^{-3}. The decline in *Hylocomium splendens* in response to air pollution was noted by Porley & Hodgetts (2005, pp. 204) and experiments in Europe have confirmed a strong link with N eutrophication (Dirkse & Martakis, 1992; Hallingbick, 1992; Strengbom *et al,* 2001; Koranda *et al,* 2007).

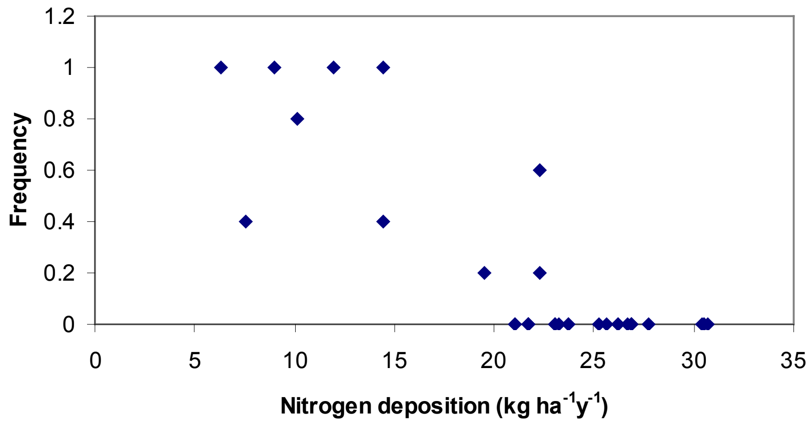

Figure 5.5. Frequency of Hylocomium splendens in 36 Calluna moorlands sites in relation to modelled N deposition (Air Pollution Information System) in northern Britain 2005-6 (Data of Edmondson 2007 and Caporn *et al,* 2007).

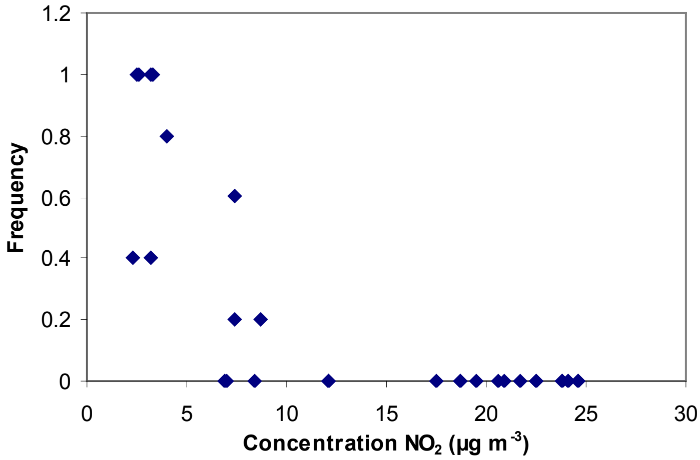

Figure 5.6. Frequency of *Hylocomium splendens* in 36 *Calluna* moorlands sites in relation to modelled N dioxide concentration (Air Pollution Information System) in northern Britain 2005-6 (Data of Edmondson 2007 and Caporn *et al,* 2007).

Liverworts were recorded at most of the regional survey sites and a greater diversity were recorded in low N deposition sites (section 6), but individual species, the most common being *Lophocolea bidentata,* were highly variable, and not consistently present at either high or low N deposition sites. Similarly, the diversity of vascular plants were much greater in the Scottish than either the Welsh or Pennines locations (see section 6) but no individual species were recognised as reliable indicators because of their highly variable occurrence or owing to their general northern or local distribution (e.g. *Arctostaphylos uva-ursi, Vaccinium vitis-idaea, Trientalis europaea).*

5.4.3 Summary of plant species data in experiments and regional surveys on upland dry heath

Table 5.8 Potential indicators of N deposition in heathland.

Species	Ellen-berg	Nitrogen experiments	Regional survey	Other evidence	Easy of identification	Suitable indicator
Cladonia lichens	n.a.	Decline (Ruabon)	Decline	Yes (1)	*Cladonia portentosa* is easy	Good
Hylocomium splendens	2	Not present	Decline	Yes (2, 3, 4, 5)	Easy	Good
Dicranum scoparium	2	No effect	Decline		Moderate	Poor – (but see sec 4)
Campylopus flexuosus	1	Decline	Inconsistent		Difficult	Poor
Lophozia ventricosa	2	Decline	Inconsistent		Difficult	Poor

Lophocolea bidentata	2	Decline	No effect		Moderate	Poor, occurs across range
Hypnum jutlandicum	2	Decline (Ruabon) Increase (Budworth)	Decline	Yes	Easy with guidance	Poor, occurs across range
Eurhynchium praelongum	5	No effect	No effect		Difficult	Poor
Calluna vulgaris	2	Increase & decrease (Ruabon & Budworth)	No effect	Yes	Easy	Poor

Ellenberg N values for Bryophytes taken from 'Bryoatt' (Hill *et al,* 2007). References: (1) Hyvarinnen & Crittenden, 1998; (2) Koranda *et al,* 2007 (3) Strengbom *et al,* 2001; 4) Dirkse & Martakis, 1992 (5) Hallingbick, 1992.

The Ruabon N manipulation experiments and the regional surveys of comparable moorland habitat generated one clear outcome - that the overall abundance and diversity of moss, liverworts and lichens are negatively affected by N pollution. However, there are only a few clear messages from the two scientific approaches regarding reliable species indicators (Table 5.8). The lichen genus *Cladonia* and moss *Hylocomium splendens* emerged from the regional survey along with supporting research as candidate clean air indicators (i.e. negative indicators of N pollution). Both the experiment and the regional survey scored the genus *Cladonia*, but of these *C. portentosa* is easily the best candidate because of its visibility and relative ease of identification.

As well as *Hylocomium splendens*, another moss appearing to be pollution sensitive from the regional survey was *Dicranum scoparium*. However, neither of these mosses were confirmed as sensitive in the Ruabon experiment because *H. splendens* was not present at the site and *D. scoparium* showed no consistent responses to N treatments (apart from a decline only at the highest addition rate). Further survey work is recommended to substantiate these species relationships with N pollution.

The lack of consistency between the experiments and the regional survey was true for other species frequently recorded in the Ruabon experiment (such as *Pohlia nutans*, *Campylopus flexuosus, Lophozia ventricosa, Lophocolea bidentata*) where presence in the regional survey was infrequent ('patchy') or they were found across the whole deposition range. One moss abundant in both the experiments at Ruabon, Budworth and in the regional surveys is *Hypnum jutlandicum* and, on the basis of both approaches, is found across the range with some preference for medium levels of N deposition. The N addition experiment to a lowland bog at Whim has found *Hypnum jutlandicum* to be fairly insensitive to N addition (Lucy Sheppard, CEH, Edinburgh - personal communication). The only candidate indicator of polluted conditions was the moss *Eurhynchium praelongum* which is known to favour nutrient enriched sites, and was fairly insensitive to N additions at Ruabon. However, it was common right across the deposition range in the regional survey with some preference shown for the more polluted locations (see section 6).

The dominant plant *Calluna vulgaris* was at times enhanced by N additions and at other times was suppressed, depending on the stage in the life cycle. The regional survey sites were selected for their good quality heather cover so abundance of the dominant species cannot be used, in this case, as a marker of air pollution. The coverage of *Calluna* on moorlands is probably and typically more strongly related to land use and management than to air pollution.

5.5 Woodland indicators

Woodland indicators have been identified by survey of available literature thus if there was an increase or decrease in indicators this could be taken as enrichment. Several studies have been conducted in Europe to identify potential indicators of N deposition in Europe. Kirby *et al* (2005) conducted a re-survey of 103 woodland plots that were originally surveyed in 1971. A total of 1610 plots were examined across England, Scotland and Wales. They examined flora and soil chemistry in each of the plots. The study found increases in a number of plants of more fertile conditions that showed a significant correlation with modelled N deposition. Plant species increasing in cover were *Poa nemoralis/trivialis*, *Galium aparine*, *Allium ursinum*, *Athyrium filix-femina*, *Carex pendula* and *Urtica dioica*. Species that decreased in cover with increasing N deposition were *Deschampsia flexuosa*, *Agrostis capillaris*, *Ajuga reptans*, *Holcus lanatus*, *Pteridium aquilinum* and *Vaccinium myrtillus*. The Ellenberg values and FNIS scores (see below) were all consistent with the changes observed for these species. Findings of Strengbom *et al* (2003) were in agreement but in contrast Nordin *et al* (1998) found not short-term response to N deposition for *Deschampsia flexuosa* or *Vaccinium myrtillus*.

In a less extensive study Mitchell *et al* (2005) examined epiphytic moss, liverwort and lichen communities in Atlantic Oak woodlands in Scotland and the north of England. They found that bark pH and ammonium concentration in the stemflow explained the greatest amount of variation in the species composition among the sites they investigated. They were able to identify a number of species that were either positively or negatively correlated with N deposition. Potential indicators of low N deposition were *Isothecium myosuroides* and *Frullania tamarisci*. Species associated with the high pollution site were *Hypnum andoi*, *Cladonia coniocraea*, *Hypotrachyna laevigata*, *Hypogymnia physodes*. The authors showed that the highest levels of deposition were actually relatively low compared to other parts of the UK meaning that these indicators were probably only suitable for use in Atlantic oak woods which have a restricted distribution. Additionally in experimental N additions in the Netherlands at levels of 30-60 kg N ha^{-1} yr^{-1} investigating the effect of N deposition on woodland bryophytes Dirkse and Martakis (1992) found *Hylocomium splendens* and *Pleurozium schreberi* declined strongly. However, these levels are high in comparison to UK deposition levels.

Diekmann and Falkengren-Grerup (1998) describe a functional index (FNIS) for forest species in central Europe that is based on mineralization rates of different forms of soil N. They describe the index as “a good and generally applicable expression of the species responses to N availability in deciduous forest soils”. This method has not been tested for its suitability in the UK but does allow identification of a number of potential N deposition indicators (i.e. those with a low FNIS score). Species in their study that score in FNIS classes 1 or 2 and thus are related to low N availability are: *Carex pilulifera*, *Deschampsia flexuosa*, *Pteridium aquilinum*, *Trientalis europaea*, *Vaccinium myrtillus* and *Vaccinium* *vitis-idaea*. A second index (Diekmann and Falkengren-Grerup, 2002) is based on mineralisable N at a given pH but has only been examined in Sweden.

The response of the herbaceous layer in woodland ecosystems to N deposition is complex, influenced by both direct and indirect factors. Gilman (2006) identify interspecific competition, changes in herbivory, changes in mycorrhizal infection, pathogenic fungal infection, species invasions and exotic earthworm activity as all interacting with N deposition.

Given the findings above there are a number of species that could potentially be added to CSM guidance as positive or negative site condition indicators of N deposition in woodlands:

Table 5.9. Positive site condition indicator species in woodlands for atmospheric N deposition and supporting evidence.

Species	**Reference**	**Ellenberg score**	**FNIS value**	**Ease of identifi-cation**	**Suitability as indicator**
Deschampsia flexuosa	Kirby *et al* (2005) Diekmann and Falkengren-Grerup (1998) Nordin *et al* (1998) Strengbom *et al* (2003)	Low	Low	Easy	Poor – not an indicator in all woodland types
Agrostis capillaris	Kirby *et al* (2005)	Low	Low	Easy	Good
Ajuga reptans	Kirby *et al* (2005)	Moderate	-	Easy	Possible – contradictory evidence
Holcus lanatus	Kirby *et al* (2005)	Moderate	Low	Easy	Good
Pteridium aquilinum	Kirby *et al* (2005) Diekmann and Falkengren-Grerup (1998)	Low	Low	Easy	Good
Vaccinium myrtillus	Kirby *et al* (2005) Diekmann and Falkengren-Grerup (1998) Nordin *et al* (1998) Strengbom *et al* (2003)	Low	Low	Easy	Good
Isothecium myosuroides	Mitchell *et al* (2005)	-	-	Fairly easy	Good
Frullania tamarisci	Mitchell *et al* (2005)	-	-	Moderately difficult	Poor – rare in south

Table 5.10. Negative site condition indicator species in woodlands for atmospheric N deposition and supporting evidence.

Species	Reference	Ellenberg score	FNIS value	Ease of identification	Suitability as indicator
Poa nemoralis/ trivialis	Kirby *et al* (2005)	High	High	Fairly easy	Poor – not an indicator in all woodland types
Galium aparine	Kirby *et al* (2005)	High	High	Easy	Poor – not an indicator in all woodland types
Allium ursinum	Kirby *et al* (2005)	High	-	Easy	Poor – not an indicator in all woodland types
Athyrium filix-femina	Kirby *et al* (2005)	High	High	Easy	Poor – not an indicator in all woodland types
Carex pendula	Kirby *et al* (2005)	High			Poor – not an indicator in all woodland types
Urtica dioica	Kirby *et al* (2005)	High	High	Easy	Localised patches frequently associated with intense enrichment (e.g. eutropic ditches)

Without detailed analysis of the data it is difficult to determine if presence or absence of these species is sufficient to determine the impact of N deposition or if more detailed occurrence data would need to be collected. We are also unable to determine how quickly these species respond to N deposition and whether the response is the same in different woodland communities. Without further evidence and analysis of other influences the impact of N deposition could only be determined if, on a site, a suite of these indicators started to increase in abundance and there was a reasonable suspicion that no other point or run-off related sources of N were apparent. As there are currently no positive or negative indicator species in the current guidance adding then may be more problematic than in other habitats.

There are also some specific considerations regarding the use of indicator species for N deposition in woodlands. The first of these is that there are shifts in nutrient and acidity levels during the woodland cycle, for example gaps tend to be richer and less acidic than the closed canopy phase. In woodland ground flora species that increase with higher nutrients also tend to increase with increased light levels. Past management may have depleted nutrient level so as in other habitats an increase in nutrient levels may be due to a change in management. There may also be interactions with grazing of deer (Kirby, personal communication).

6 How can changes in other attributes be used?

6.1 Detecting nitrogen deposition

6.1.1 Acid grasslands

Species data from the Stevens (2004) survey were analysed for species richness and percent cover of the following species groups: total species, grasses, sedges, rushes, graminoids, forbs, legumes, shrubs, tree seedlings, mosses and liverworts, pleurocarpous mosses and acrocarpous mosses. Grass:forb ratios, gramnoid:forb ratios and fine:broad leaved grass were also calculated using percent cover data. Data from CCW (2004) could only be analysed for richness variables because only domin values were available as a measure of cover. These data sets were examined using regression analysis with N deposition as the independent variable and species variables as dependent variables. N deposition was modelled by CEH Edinburgh as outlined in section 5. Clear and statistically significant trends in the data are outlined below.

The strongest trend between species variables and N deposition was with species richness (mean of 5 2x2m quadrats placed randomly within 1ha) (Figure 6.1). Regression analysis showed a statistically significant negative correlation between N deposition and species richness (r^2=0.52; p<0.01).

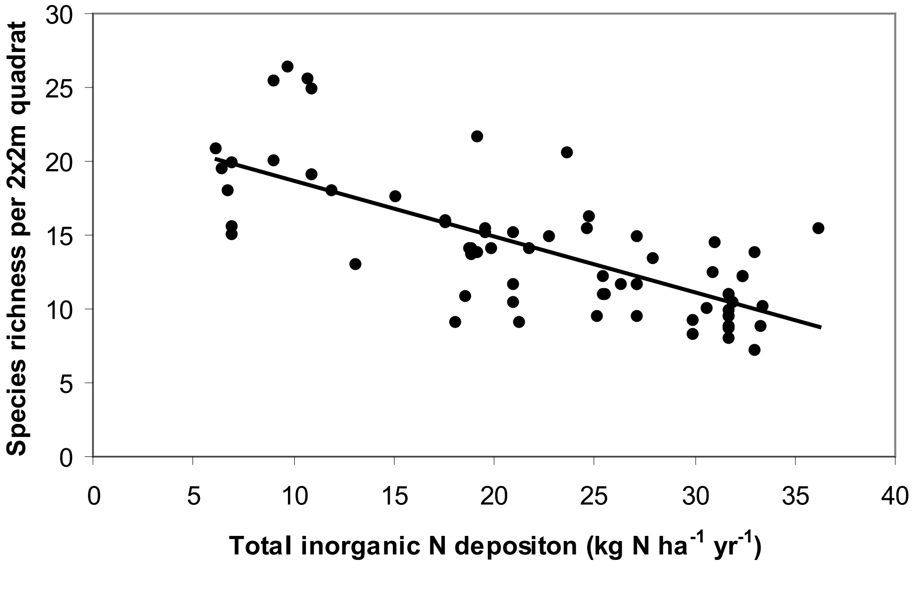

Figure 6.1. Relationship between species richness and total inorganic N deposition (Stevens *et al,* 2004).

This relationship is discussed in detail by Stevens *et al* (2004). Mean annual precipitation and altitude were found to explain additional significant variation.

Investigating the relationship between species richness and N deposition in the Welsh lowland grassland survey data shows slightly different results. Numbers of quadrats per site ranged from 1 to 14 so these were combined to give average site richness where possible. The results did not show a significant relationship between species richness and N deposition for all acid grassland communities analysed together, however, given that data were collected over a period of 20 years, changes in community composition over time could mask other trends. For U1 grasslands there was a statistically significant negative relationship between species richness and nitrogen deposition (r^2=0.17, $p<0.05$). There were insufficient data points for U2 or U3 grasslands. For U4 grasslands there was no significant relationship between deposition and species richness.

The countryside survey data (2003) showed a significant relationship between N deposition and species richness (r^2=0.04, $p<0.001$) (Figure 6.2) and although this was much weaker than in the Stevens (2004) data, given the problems of classifying these grasslands in countryside survey data, that a trend is detected at all would suggest that it is real.

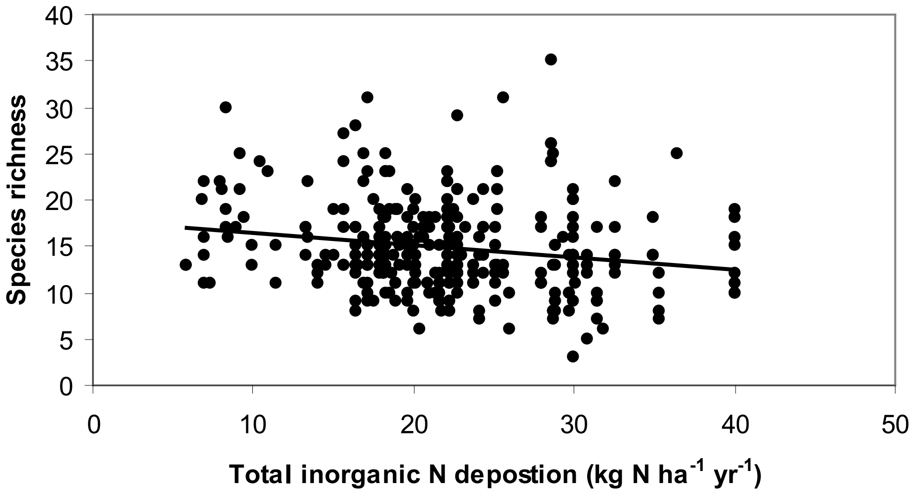

Figure 6.2. Relationship between species richness and total inorganic N deposition in countryside survey data.

Species richness would appear to be a good indicator of N deposition although without further investigation we cannot tell if the number of species is responding to current deposition or cumulative deposition. Data to determine this are not currently available. Monitoring or experimentation over time would be needed to determine how quickly these grasslands respond to changes in N deposition. Work is underway as part of the NERC/ESF project BEGIN to address this and information should be available in the next year.

Although species richness would appear to be a good indicator of N deposition, there are some drawbacks. Species richness is also governed by many different factors (including management), so care would need to be taken in interpreting the data. For example, species richness shows a typically unimodal relationship with the full length of the substrate productivity gradient, hence the expected direction of change needs to be supported by carefully establishing the starting community type i.e. being certain the monitored stand qualifies as acid grassland. It is also time consuming to collect and requires a trained botanist. Species do not need to all be identified as in a Phase 2 survey but there is a need to distinguish all species, including mosses and grasses. This probably makes it prohibitively time consuming for incorporation into CSM, but the value of species richness as a potential indicator should be considered. Setting a level of species richness to indicate habitats that are negatively impacted by N deposition is hard with these trends, but a richness of below 10 species per 2x2m quadrat is consistently associated with higher N deposition in both data sets.

Of the other species richness variables investigated in the Stevens *et al* (2004) data set forb richness showed the strongest relationship with N deposition (Figure 6.3).

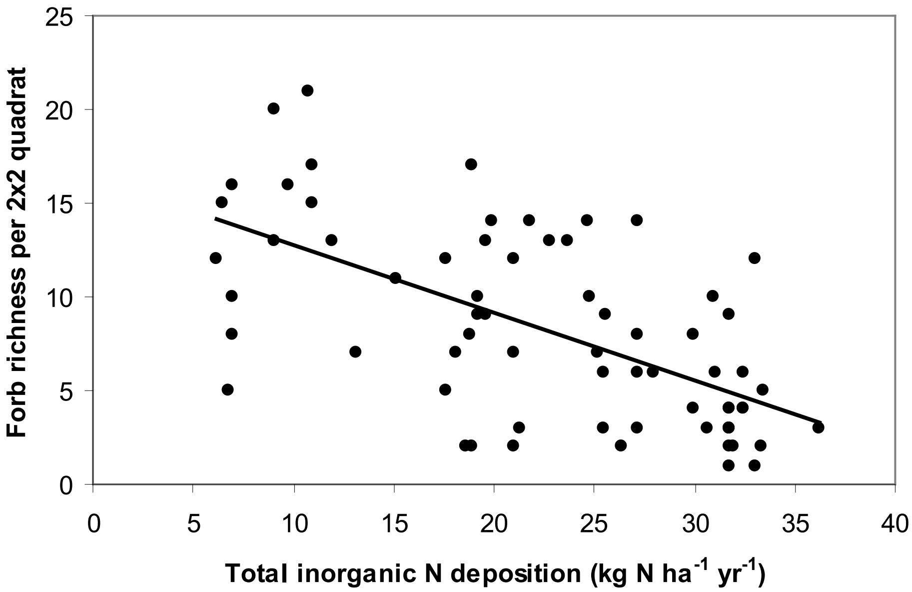

Figure 6.3. Relationship between forb richness and total inorganic N deposition (Stevens *et al,* 2006).

Although less of the variation in forb richness is explained by N deposition in this analysis the gradient of the decline in richness is steeper and the relationship is highly significant (r^2=0.38, p<0.001).

Forb richness also shows a significant relationship in countryside survey data (r^2=0.04, p<0.001) (Figure 6.4).

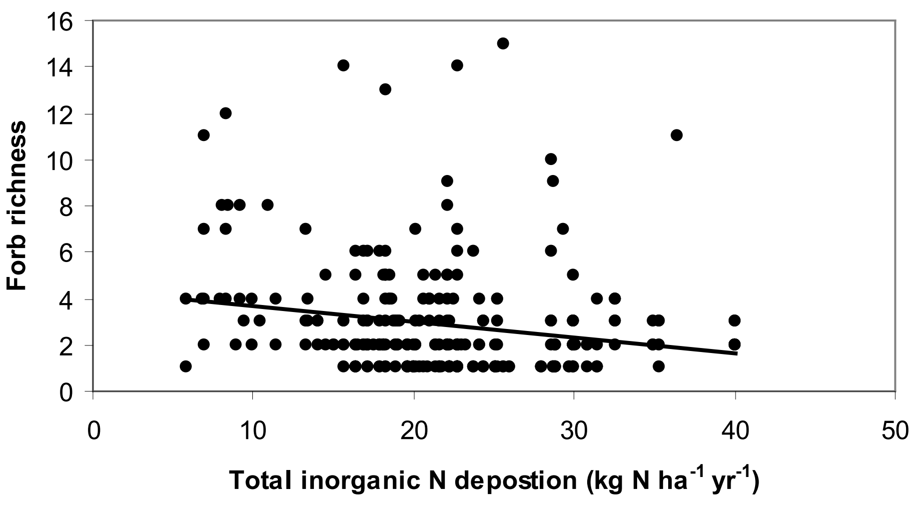

Figure 6.4. Relationship between forb richness and total inorganic N deposition in countryside survey (2003) data.

Although using forb richness does not overcome some of the difficulties associated with measurement of species richness it is much easier to assess. Forbs are generally much easier to distinguish than mosses and graminoid species. The large number of low values in the distribution potentially makes it more difficult to interpret than species richness and to set a threshold level. A forb richness of below 4 could be taken as indicative of N deposition impacts although these levels occur in some low N deposition sites.

Richness of Pleurocarpous mosses (Figure 6.5) also showed a significant relationship with N deposition in the Stevens (2004) data set, however this relationship was not as strong as with either forb or species richness (r^2=0.10, p<0.01).

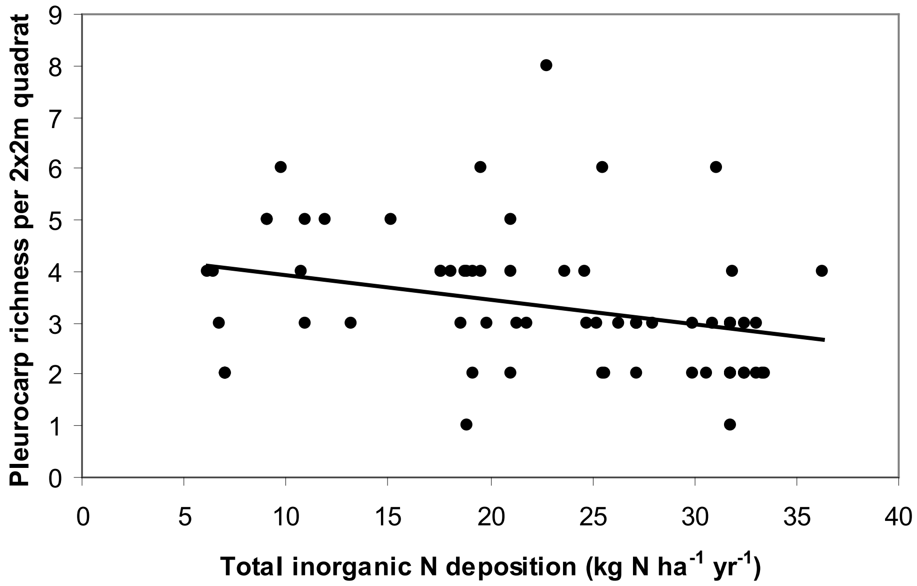

Figure 6.5. Relationship between pleurocarpous moss richness and total inorganic N deposition.

Although the relationship for pleurocarpous moss richness is clear, these data would be difficult to collect. In addition to the problems of collecting richness data described above finding mosses in a closed sward requires careful attention and specialist knowledge is needed to distinguish species.

Cover of groups provides an alternative to richness. Cover is potentially quicker and easier to estimate than richness although this is not always the case in complex grassland swards.

In the Stevens (2004) data set, forb cover also showed a significant relationship with N deposition (r^2=0.42, p<0.001) (Figure 6.6).

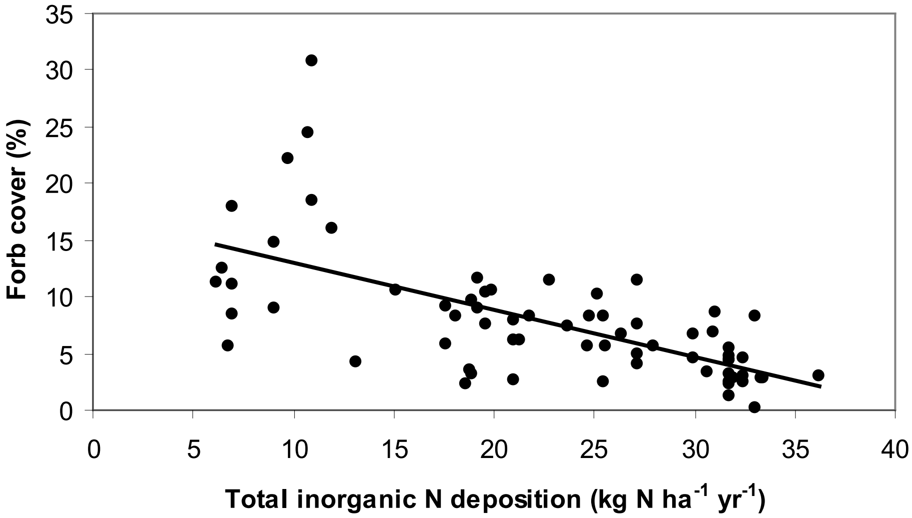

Figure 6.6. Relationship between forb cover and total inorganic N deposition in Stevens data.

Forb cover of less than 5% could be taken as indicative of N deposition however, forb cover did not show a significant relationship in the countryside survey data (r^2=0.002, p<0.36) suggesting it is not a robust indicator.

Using percentage cover of other groups did not reveal any significant trends. Ratios (based on percentage cover) were also examined and revealed several potentially interesting relationships.

Grass:forb ratio shows a significant positive relationship (p<0.05) with N deposition in the Stevens (2004) data set (Figure 6.7). This relationship shows that at the highest levels of N deposition, the grass:forb ratio tends to increase suddenly indicating that this may be an indicator of the sites most severely affected by N deposition. Fitting an exponential relationship gives an r^2 of 0.33 but this relationship is strongly driven by a sudden increase in the ratio at 32kg N ha^{-1} yr^{-1}.

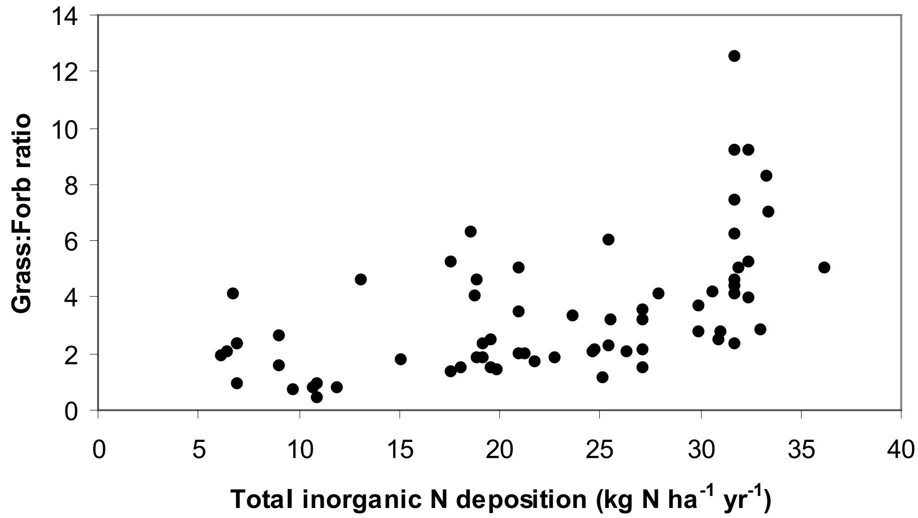

Figure 6.7. Relationship between grass:forb ratio (% cover) and total inorganic N deposition in Stevens (2004). An outlier (high ratio at high N deposition) has been removed from the graph for the pattern to be clearly visible.

Grass:forb ratio also showed a significant relationship (r^2=0.05, p<0.001) with N deposition in countryside survey data (Figure 6.8).

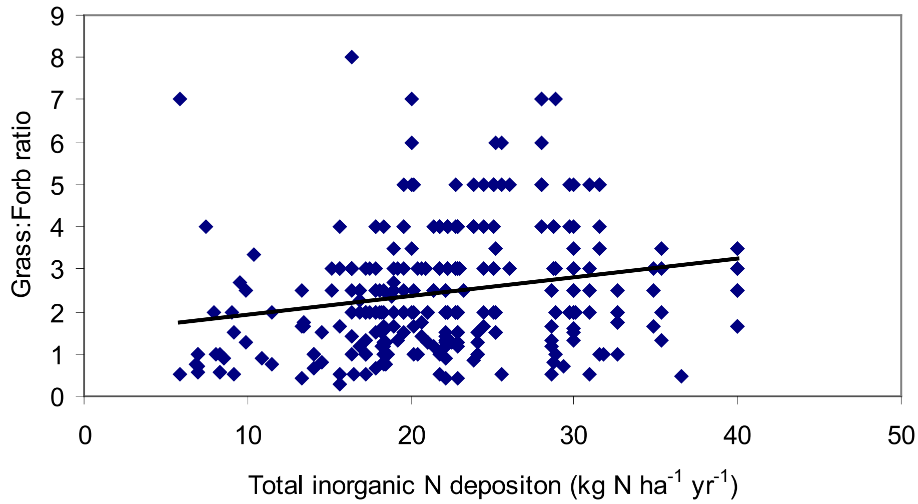

Figure 6.8. Relationship between grass:forb ratio (% cover) and total inorganic N deposition in countryside survey data.

Although there is a less clear trend in the countryside survey data the levels of the grass:forb ratios are similar between the two data sets. In both data sets a grass to forb ratio of above 5 could be taken as indicative of higher levels of N deposition. Grass:forb ratio may vary considerably over a site and several estimates would need to be made, it will also vary with time of year and should only be estimated during the summer, as this is when these data were gathered.

Grass cover itself may be quite hard to reliably estimate, as there are many other gramnoid species (sedges and rushes) that look like grasses without close inspection.

An alternative to a grass:forb ratio is a gramnoid to forb ratio where the cover of grasses, sedges are all included together. Although sedges may not show a response to N deposition alone they are a small component of the vegetation so the combined cover shows a very similar pattern (r^2=0.07, p<0.05) to the grass to forb ratio (Figure 6.9) and may provide a good alternative.

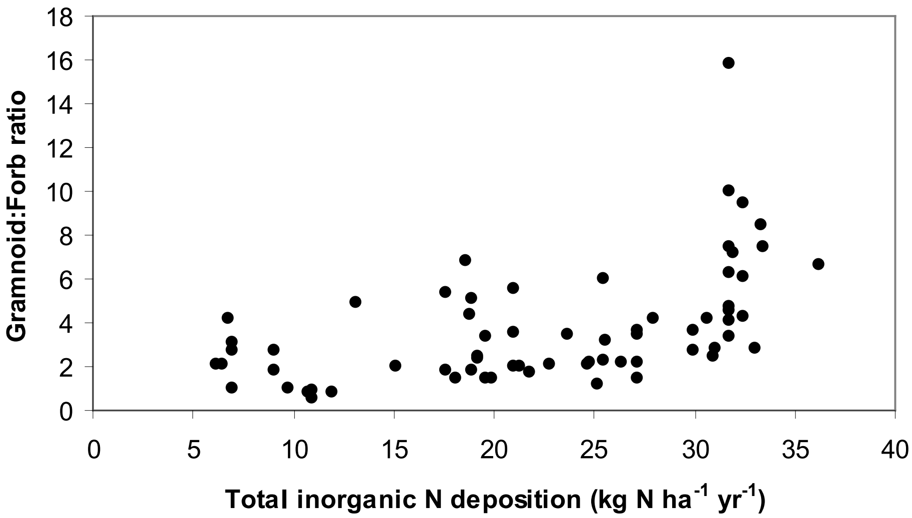

Figure 6.9. Relationship between graminoid:forb ratio (% cover) and total inorganic N deposition. An outlier (high ratio at high N deposition) has been removed from the graph for the pattern to be clearly visible.

A very similar pattern to grass:forb ratio was also seen in the countryside survey data (r^2=0.05, p<0.001). A graminoid:forb ratio of above 5 could also be used to indicate high N deposition. However for both these ratios, the increase is only obvious above a N deposition of 30 kg ha^{-1} yr^{-1}, well above the acid grassland critical load of 10-20 kg ha^{-1} yr^{-1}. Care should be taken in the use of such ratios because ratios will change in different seasons due to differing phonologies of the species.

The final ratio that showed statistically significant results is the fine leaf:broad leaf grass ratio (r^2=0.08, p<0.05). This showed a higher ratio (*i.e.* higher cover of broad leaved grasses) at high N deposition. This relationship was not as strong as the grass to forb ratios. This is less suitable as an indicator because it is difficult to estimate cover without identifying the species in a grazed habitat such as this. Some of the broad leaved grasses (such as *Agrostis capillaris*) can appear very fine and without close examination are easily mistaken for fine leaved grasses.

Individual species did not make good indicators based on presence absence alone because all of the species identified as indicators of N deposition occurred across the whole range of N deposition but cover of individual species may provide better evidence of N deposition. Stevens (2004) data are used for this analysis because this is the only data set providing reliable % cover data. Species identified as potential indicators in section 2 but discarded because they were found across the range of deposition are shown in graphs against total inorganic N deposition in Figure 6.10.

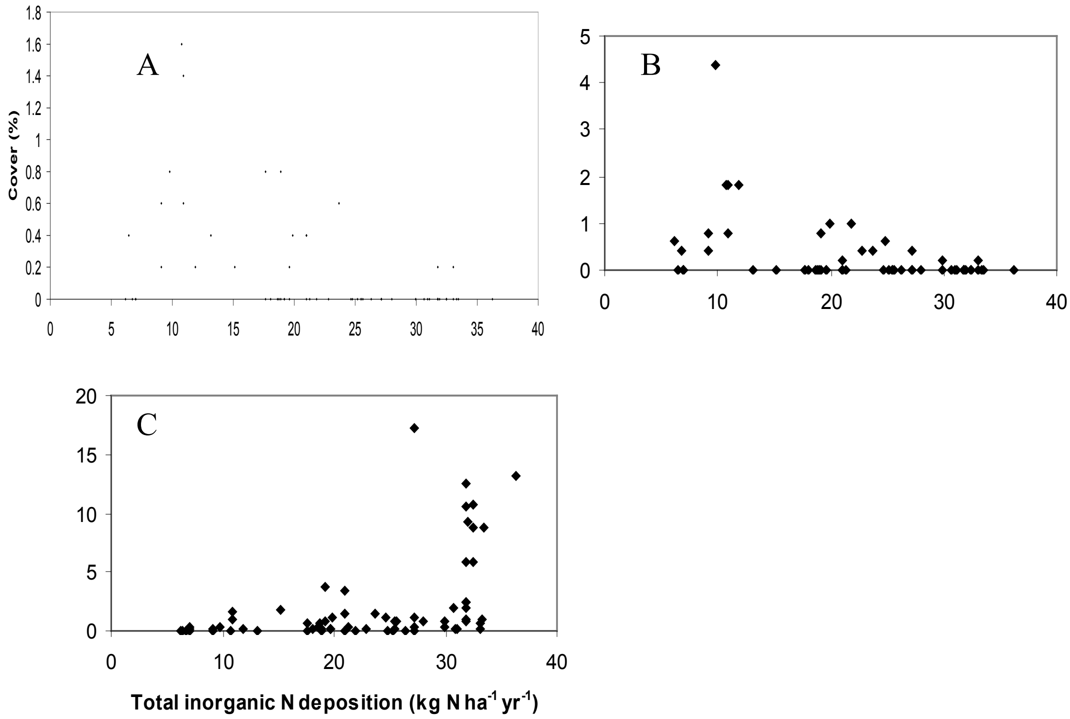

Figure 6.10. Percent cover against N deposition for potential positive site condition indicators **A**. *Campanula rotundifolia*, **B**. *Euphrasia officinalis*, and potential site condition negative indicator **C**. *Hypnum cupressiforme*. Note that the scale of percentage cover axes vary between graphs.

Figure 4.10 shows that some species would make much better indicators than others. An average cover of *C. rotundifolia* of over 0.5% would seem to be a fairly good indicator of low N deposition. However, there are quite a few sites with low deposition where this species has low cover or where it is absent. It is also extremely difficult to estimate this low cover. The same is true of *E. officinalis* which also occurs at low cover. *Hypnum cupressiforme* could potentially be used to identify sites with the highest levels of N deposition. Cover of over 5% is only found at sites with the highest levels of deposition. Some high deposition sites are not identified by this; estimating the proportion of moss cover that is accounted for by *Hypnum* may provide a better indicator, however the work involved in doing this in the field is likely to be prohibitive for CSM. The final negative site condition indicator is *C. panicea* which contains too many absences or very low cover values to be useful as an indicator.

A summary of potential indicators for acid grasslands is given in Table 6.1.

Table 6.1. Indicators of positive and negative site condition related to N deposition in acid grasslands. Ticks for each survey indicate a consistent Message.

Indicator	Level	CCW	CS	Stevens	Ease of use
Vegetation species richness (average for 5 2x2m quadrat)	<10	Partial	✓	✓	Time consuming and specialist knowledge needed
Forb species richness (average for 5 2x2m quadrat)	<4	X	✓	✓	Time consuming and requires some specialist knowledge
Forb cover (%)	<5	-	X	✓	Potentially difficult in complex swards
Grass:forb (% cover)	>5	-	✓	✓	Not easy to separate grasses and sedges
Graminoid cover: forb cover (%)	>5	-	✓	✓	Easier to estimate
Hypnum cupressiforme cover (%)	>5	-	-	✓	Difficult to estimate and may be absent for other reasons

6.1.2 Bogs

Countryside survey species data from 1998 were analysed for species richness and percent cover of the following species groups: total species, grasses, sedges, rushes, graminoids, forbs, woody species and mosses. Grass:forb ratios and graminoid:forb were also calculated.

Species richness was again the strongest signal in the data and showed a negative relationship with nitrogen deposition ($p<0.001$) (Figure 6.11). Again the r^2 value was low (0.08) but the data are extremely variable with a long N deposition gradient, and unlike an experiment testing a specific hypothesis controlling for explanatory variables we are detecting a signal in the real world.

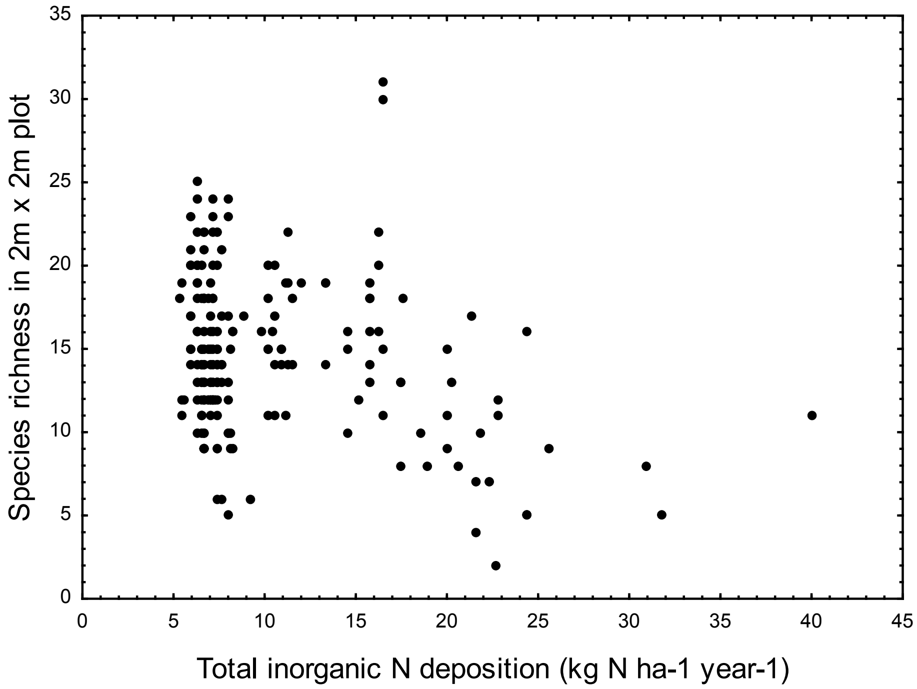

Figure 6.11. Relationship between species richness and total inorganic N deposition in Countryside survey (2003) data.

When broken down into groups i.e. forbs, mosses, grasses, woody species, sedges, monocots there were no significant relationships between group richness and N deposition. There was a negative relationship between N deposition and the number of forbs but it was not quite statistically significant.

However, total vegetation cover was significantly related to N. Total cover showed a positive relationship with N deposition (r^2=0.03, p<0.05) (Figure 6.12).

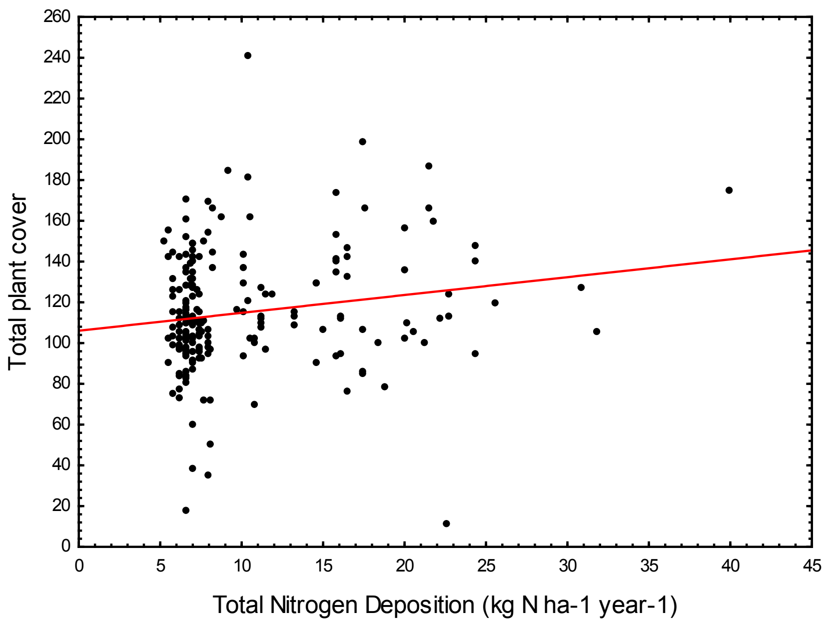

Figure 6.12. Relationship between total plant cover and total inorganic N deposition in Countryside Survey data.

When analysed separately forb cover increased with N deposition (r^2=0.03, $p<0.05$), as did grass cover (r^2=0.03, $p<0.05$) and monocot cover (r^2=0.06, $p<0.001$).

There was a significant relationship in the countryside survey data between the grass: forb ratio and N deposition in bogs when cover was log transformed ($r^2 = 0.06$; $p < 0.001$) (Figure 6.13). However there was no significant relationship when sedges were also added i.e. between graminoid:forb ratio and N deposition. As above with acid grasslands there may be some potential in measuring the grass:forb ratio at a site to determine nitrogen impact.

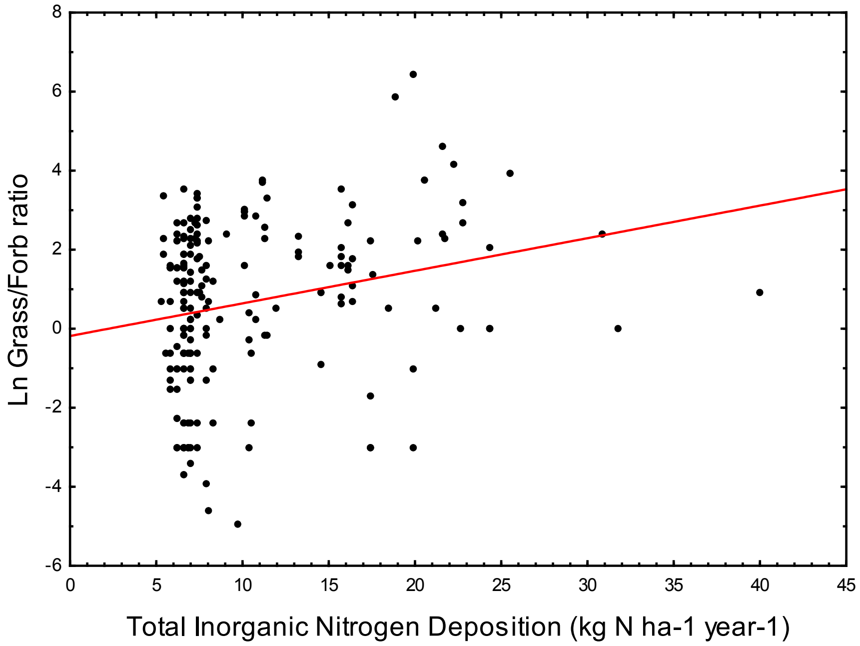

Figure 6.13. Relationship between log grass forb ratio and total inorganic N deposition in Countryside Survey data.

Log cover for species chosen as indicators in question 3 was plotted against N deposition. There were significant positive relationships between log cover of *Molinia caerulea* (r^2=0.11, $p<0.001$), *Vaccinium myrtillus* (r2=0.32, p<0.001) and *Polytrichum commune* (r^2=0.4, $p<0.05$) and N deposition (Figure 6.14).

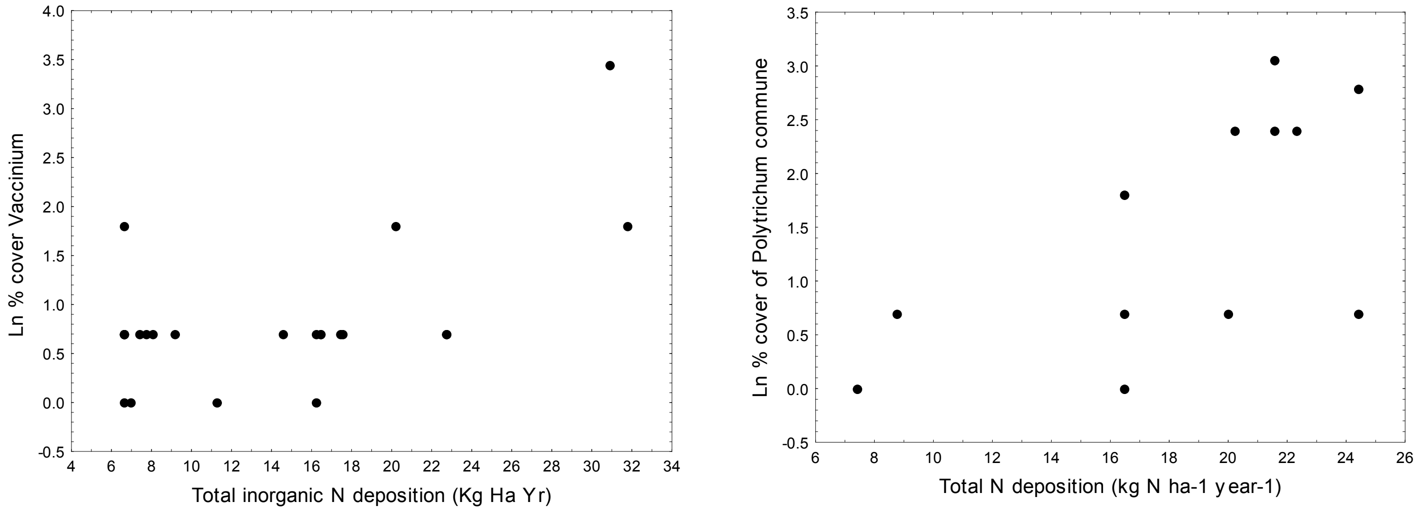

Figure 6.14. Log percent cover against N deposition for potential positive site condition indicators *Vaccinium myrtillus* and *Polytrichum commune.*

There was no significant relationship between the cover of small species such as *Drosera rotundifolia, Pinguicula vulgaris, Pedicularis sp.* and N deposition, unsurprisingly since these species contribute little in terms of cover.

It does appear that as N deposition increases in these bog communities the growth of particular species (*Molinia caerulea, Deschampsia flexuosa, Vaccinium myrtillus*) is stimulated which may shade out species preferring higher light conditions (e.g. *Drosera* sp., *Pedicularis* sp., *Dactylorhiza maculata*- all have Ellenberg light score >7). The grazing regime at the site will also have to be considered as a factor interacting with N deposition. Observations from the southern Pennines blanket bog bryophyte surveys of Caporn *et al* (2006) discussed in detail in section 5.3, support the view that reductions in air pollution are related to increasing bryophyte species richness on bogs. Between the 1980s and 2005-6 there was a large increase in all bryophyte groups, particularly in the liverworts which were not found in the earlier survey (Figure 6.15). The recovery of liverworts in the southern Pennines is interesting as these were found to be significantly increasing in the Ruabon heath experiment two years after halting of N additions to half of each of the plots (see section 5.4.1 and Edmondson, 2007).

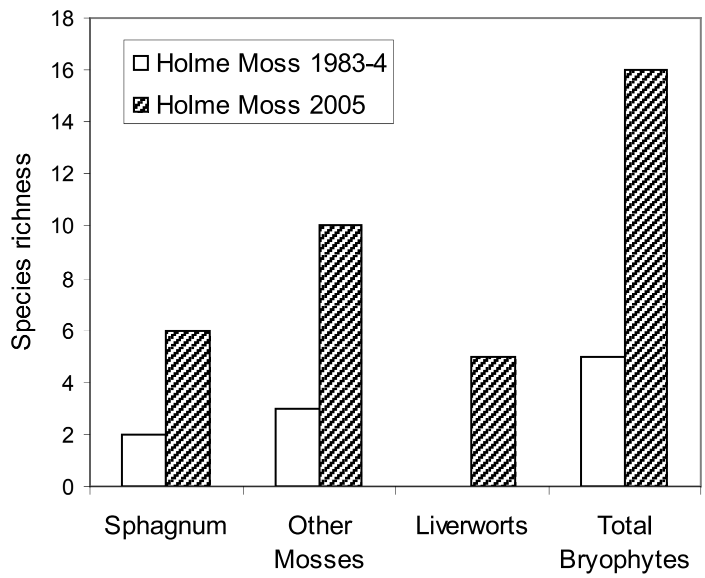

Figure 6.15. Increase in the number of species of *Sphagnum*, other mosses and liverworts in open plots on ombrotrophic blanket bogs at Holme Moss in the southern Pennines between 1983-5 and 2005-6 Very similar results were gained from surveys at nearby Alport Moor (Caporn *et al,* 2006).

Despite the marked improvement in bryophytes in the southern Pennine blanket bogs, there remains rather low species richness and very low abundance of most of those present compared with similar bogs at similar latitudes and climates (e.g. in north Wales). The slow recovery of the southern Pennine bogs may be due to the continuing high rates of N deposition and the legacy of sulphur, N and metal that remains stored in the peat.

Table 6.2. Indicators of positive and negative site condition related to N deposition in bogs. Ticks for each survey indicate a consistent Message.

Indicator	**Level**	**CS**	**Ease of use**
Vegetation species richness	<5	✓	Time consuming and specialist knowledge needed
Bryophyte richness		X	Mixed evidence that bryophyte richness is negatively related to N. Requires good ID skills.
Total cover (vegetation structure)	>110	✓	Easy to estimate
Grass:forb (% cover)	>1	✓	Not easy to separate grasses and sedges
Vaccinium myrtillus cover (%)	>5	✓	Easy to estimate
Polytrichum commune cover (%)	>5	✓	Easy to estimate

6.1.3 Dwarf shrub heath

Data from the Ruabon N addition experiments (e.g. Carroll *et al,* 1999; Edmondson, 2007) and the *Calluna* moorland surveys (Edmondson 2007, Caporn *et al,* 2007) were explored to find further potential botanical indicators. Details of the experiment and survey methods and many of the results are given in section 5.4.

6.1.4 Experimental nitrogen addition to upland dry heath at Ruabon

The cover of total mosses was generally lower in the N treatments compared with the control up to the year 2000 (Figure 6.16). However, N treatment increased ageing of the *Calluna* canopy and in the highest treatment there was some recovery of moss cover as light penetrated through the canopy gaps (see the far right bars in each year before 2000). Following the managed burn in 2000 (Pilkington *et al,* 2007), the bryophyte cover increased, mainly as *Campylopus* mosses, probably due to access to light and nutrients (e.g. phosphate and potassium) released from the ash.

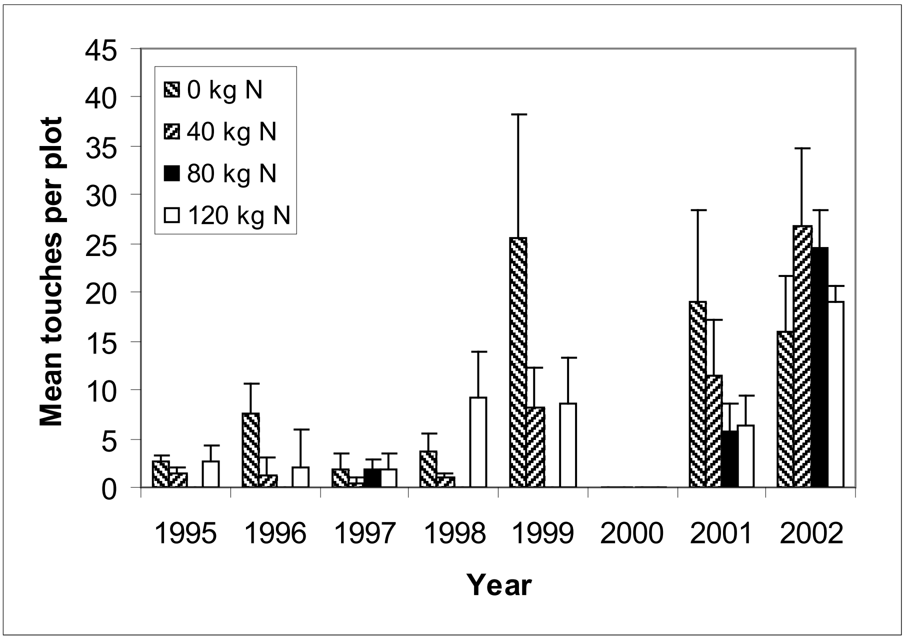

Figure 6.16. Moss cover in response to N addition (0-120 kg ha^{-1} y^{-1}) at Ruabon in the original experiment that started in 1989. A managed burn occurred in spring 2000, so no data were collected that summer (Caporn *et al,* 2004).

The above description illustrates the problems with making general statements about bryophyte responses to N in a dynamic community. The later detailed studies on the new plots by Edmondson (2007) took place in a stable stage within a late-building/mature *Calluna* canopy. This survey in 2005 found significant reductions in abundance of all bryophytes and all mosses, but the reduction was not significant in liverworts (Table 5.5) because of block-scale variation. It is worth noting that quantitative work in both the experiment and regional study is hampered by the natural variability ('patchiness') in liverwort occurrence. The total bryophyte species diversity (Shannon-Weiner index) also declined, although this was only significant at the top N treatment (Edmondson, 2007).

6.1.5 Regional survey

In the regional surveys in 2005-6, the bryophytes were again the main focus, but a greater number of vascular plants were also recorded at some of the sites than at others and these are included in the analysis. Species level presence / absence were discussed in section 3.4.2. Here the main interest is in the potential use of species richness or relative abundance of species or groups of species to indicate N pollution.

Species richness, here meaning the total number of species at each survey site, was studied for various plant groups. Richness was correlated with modelled N deposition values and N dioxide concentrations, both accessed from the Air Pollution Information System. All correlations were negative i.e. richness decreased with increasing N pollution. The strongest linear correlations with N pollution were with (in decreasing order): all plants (vascular, bryophytes and lichens), then vascular plants, bryophytes, moss and liverworts (Table 6.3). In some cases the best correlation was with N deposition, while in others it was with nitrogen dioxide concentration.

Table 6.3. Pearson's linear correlations (r^2) between species richness of different plant groups and modelled values of N pollution or with litter % N content. The bold type highlights the strongest correlation of the three N values within each plant group.

	Nitrogen Deposition ($kg\ ha^{-1}y^{-1}$)	**Nitrogen dioxide ($\mu g\ m^{-3}$)**	**Litter N (%)**
All plants	0.613	0.633	**0.729**
Vascular plants	**0.614**	0.470	0.611
Bryophytes	0.405	0.557	**0.560**
Moss	0.299	**0.515**	0.367
Liverwort	0.198	0.136	**0.370**

Although vascular plants richness was strongly correlated with N deposition, this was due entirely to the good variety of higher plants found in the Cairngorm sites, while many of the other sites in Wales and the south Pennines had very few (0-3) vascular species (in addition to *Calluna vulgaris*). *Calluna* moorlands are managed for a dominant heather canopy and competitors are undesirable. Invasion of other vascular species sometimes occurs in less managed *Calluna* stands when they have aged and collapsed, providing the opportunity for the entry into gaps of new herbaceous species. Therefore vascular species richness in *Calluna* moorland seems unlikely to be a reliable indicator of a 'clean' site as it could just reflect poor management, indeed, Calvo *et al* (2007) show that richness increased with N, especially where there were gaps in the vegetation due to cutting or grazing.

Amongst the bryophytes, the liverworts were rather poorly correlated with N pollution because of their patchy distribution. The mosses were better correlated, while the sum of these groups, total bryophytes, was fairly well correlated with N pollution (Figure 6.17).

At each of the sites in 2006, the N content of the surface litter lying beneath the moss in the five plots was determined as a measure of the longer term N status within the soil-plant system. There was a strong correlation between N deposition and mean litter % N ($r^2 = 0.7$), and similarly a good correlation between litter % N and diversity (e.g. Figure 6.18). This is further evidence that the connection between N pollution and species richness is a causal one.

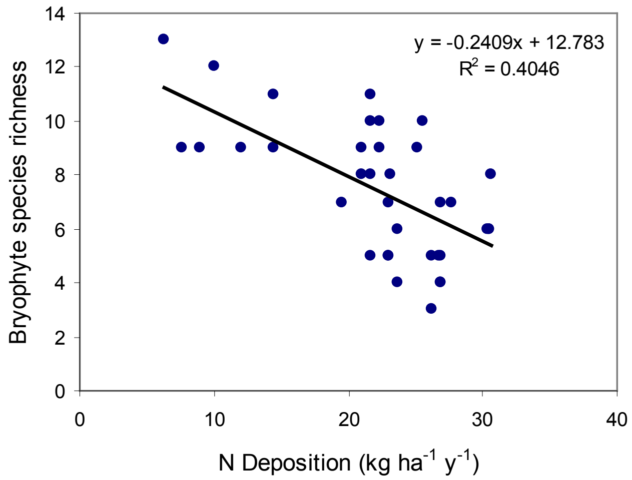

Figure 6.17. Relationship between site bryophyte species richness and modelled N deposition at 36 *Calluna* moorlands sites in northern Britain 2005-6 (Data of Edmondson 2007 and unpublished data of Carroll and Caporn).

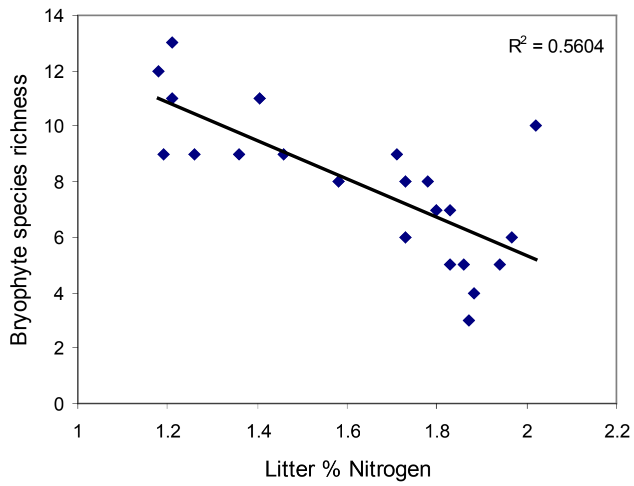

Figure 6.18. Relationship between site bryophyte species richness and litter % N content at 22 *Calluna* moorlands in northern Britain in 2006 (unpublished data of Carroll and Caporn).

While the species diversity of bryophytes on *Calluna* moorlands is a potential indicator of N deposition it is a challenging task to survey and identify all the moss and liverworts. As a research study it seems a reasonable task but for routine monitoring it is probably not. An easier approach may be to survey the abundance of particular species which are easily identified. Since not all species tend to occur at every site (irrespective of N pollution), it may be safer to monitor the collective abundance of a few strong indicators that are also easy to spot. To this end, the frequency of four moss species across all the sites was examined in relation to the three estimates of N pollution (Table 6.4).

Three of these species were found, to varying extents, across the entire range of N deposition. The other, the moss *Hylocomium splendens*, was only recorded consistently at the clean sites in Scotland (see section 5.4). The abundance of the mosses was recorded as frequency at each site and correlations with N pollution were calculated. N deposition was strongly correlated with frequency of *Hylocomium splendens,* and less well correlated with *Dicranum scoparium* and *Hypnum jutlandicum*. The only species showing a positive relationship between frequency and N pollution, albeit very weakly, was *Eurhynchium praelongum*; the other three all declined in frequency with increasing N.

Table 6.4 Pearson's linear correlations (r^2) between frequency of different species or groups of species and modelled values of N pollution or litter % N content. The bold type highlights the strongest correlation of the three N values within each plant group.

	Nitrogen Deposition (kg $ha^{-1}y^{-1}$)	Nitrogen dioxide (µg m^{-3})	Litter N (%)
H. splendens	**0.676**	0.491	0.603
D. scoparium	0.306	**0.392**	0.348
H. jutlandicum	0.131	0.087	**0.156**
E. praelongum	0.046	**0.056**	0.038
H. splendens + D.scoparium	**0.712**	0.645	0.676
H. splendens + D. Scoparium + H. jutlandicum	**0.525**	0.291	0.264

The sum of the frequency of several species was also examined and, of these, the best was the combined frequency of *Hylocomium splendens* and *Dicranum scoparium*, having a r^2 of 0.712 in correlation with N deposition, and a good correlation r^2 of 0.676 with litter % N. The summed frequency of *H. splendens, D. scoparium* and *Hypnum jutlandicum* was not as well correlated with N as just the first two of these species. These best relationships are illustrated in Figures 6.19 and 6.20.

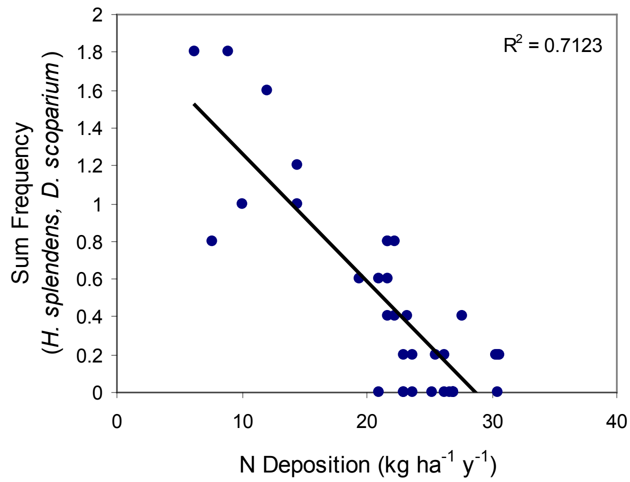

Figure 6.19 Relationship between modelled N deposition and sum of the frequency of *Hylocomium splendens* and frequency of *Dicranum scoparium* at 36 *Calluna* moorlands sites in northern Britain 2005-6 (Data of Edmondson 2007 and unpublished data of Carroll and Caporn).

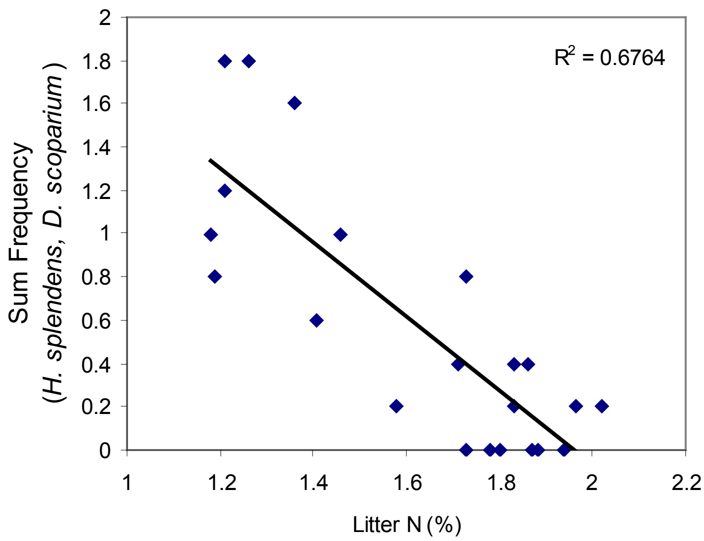

Figure 6.20. Relationship between litter % N content and sum of the frequency of *Hylocomium splendens* and the frequency of *Dicranum scoparium* bryophyte species richness and deposition at 22 *Calluna* moorlands in northern Britain in 2006 (unpublished data of Carroll and Caporn).

Table 6.5. Potential indicators of N pollution in heathlands from section 6.

Indicator	Regional Survey	Ruabon Experiment	Ease of use	Suitable as indicator
All species richness	Yes	Yes	Difficult	Costly & slow
Bryophyte species richness	Yes	Yes	Difficult	Costly & slow
Frequency *H. splendens*	Yes	No	Easy	Good
Frequency *H. splendens* and *D. scoparium*	Yes	No	Easy with guidance	Good – better than either species alone

Testing the relationships identified over a larger spatial and N deposition range and in more heathland types would give a greater confidence in the indicators presented here.

6.2 Attributing nitrogen deposition

Attributing the effects of nutrient enrichment and acidification to N deposition is very difficult because many of the effects are the same as those that would be seen from other forms of nutrient enrichment such as the application of organic and inorganic fertilisers. Where species of unimproved habitats are used as positive site condition indicators they will generally decline through the use of fertilisers as well as N deposition. To separate these effects using species composition alone is not possible. General observation of the surrounding area and identification of other nitrogen sources combined with the presence of negative site condition indicators and the absence of positive site condition indicators could be used to give a stronger indication of nitrogen source. This method could be applied to all habitat types.

Answering the following questions could be used to give an indication of whether N deposition is a threat to the site.

Indicators of other enrichment sources

- Is the site subject to flooding?

  If the site is subject to regular flooding this may bring nutrients bound to sediments on to the site enriching the soils. The nutrient status of this water and sediment needs to be determined to see if it is nutrient rich.

- Is the site fed by flushes or springs?

  If the site is fed by flushes or springs this could bring additional nutrients onto the site. If this is the case the nutrient status of this water needs to be determined to see if it is nutrient rich.

- Does the site have any previous history of fertiliser (organic or inorganic) use?

  If the site has any history of fertiliser use this is likely to have a significant impact on the nutrient enrichment. Even low levels of fertiliser addition may be equivalent to a number of years worth of cumulative deposition.

- Has the site management changed?

In some managed habitats failure to cut and remove herbage can have equivalent effects to N deposition. Reducing grazing pressure or seasonality of management may also be factors in species loss or a change in species composition. If there are indicators of inappropriate or poor management, it may not be possible to determine the impact of N deposition.

If there are other nutrient inputs or poor management, then it is unlikely to be possible to determine the impact of N deposition on these sites. N deposition is unlikely to be the most important driver of vegetation change in these situations.

Indicators of N deposition:

- Is the critical load for N deposition at the site exceeded?

If the critical load is exceeded there is a high likelihood that the habitat is under threat from N deposition. This can be calculated from APIS. Critical load exceedence should be treated with caution however, because the deposition is not modelled at a small enough scale to represent local variation. There are clearly impacts on biodiversity at lower levels and some sites at higher deposition may not be as vulnerable as expected, so it does not give a definitive answer.

- Are there point sources of N close to the site?

Point sources of ammonia can have a severe impact on sites and will not necessarily be detected in calculating critical load exceedence at a site. If there is a point source such as an intensive animal unit (e.g. poultry farm or intensive pig farm) within 500m of the site there is likely to be an impact. Larger sources are likely to have an impact at a greater distance than small sources however over 1km away sources are not likely to have an impact. Wind direction will affect how much N is deposited on a site and point sources upwind of a site will have more of an impact. Point sources of nitrogen include:

Intensive animal where animals are housed (e.g. poultry units)
Manure storage
Abattoirs
Composting facilities
Waste disposal sites

- Are there non-point sources of N in close proximity to the site?

Close proximity to non-point sources of nitrogen is also likely to result in elevated N deposition. Although non-point sources are likely to have an impact over a larger scale this is encompassed in the calculation of critical load exceedence. Important non point sources of nitrogen include:

Major roads and other areas of intensive vehicle use
Power stations
Airports
Intensive animal units (e.g. pig farms)
Areas of high fertiliser use
Manure spreading

- Is the site subject to high cloud cover?

If the site is at high altitude and subject to high cloud cover it may have high orographic deposition. This is accounted for at a larger scale in N deposition estimates for critical load exceedence but is significant if the site is in an area with very variable terrain. The high levels of N deposition are a result of enhanced rainfall and the 'seeder-feeder' effect which enhances pollutant deposition in upland areas, especially those which experience significant periods of orographic cloud cover (Taylor *et al,* 1999). Vegetation also captures wind-driven cloud droplets very effectively, and as cloud droplets can contain much higher concentrations of ions than rainwater, this is a significant source of pollutant deposition to high ground (Reynolds *et al,* 1997).

If the critical load is exceeded or there is reason to believe that deposition is higher than modelled values then N deposition could be the source of nutrient enrichment.

7 How should we test new indicators and/or attributes based on existing information?

7.1 National data sets

There are a number of data sets that could be used to test indicators. The data available differs from agency to agency and to some degree between habitats.

CSM data – existing CSM data could potentially provide a useful resource for testing indicators if they are already recorded. In Wales, Scotland and Northern Ireland these data are either held centrally or efforts are being made to compile it. If the indicators of interest have already been recorded, these would be a valuable resource; however, it is likely that they will frequently not contain sufficient information. In England, the detailed records of the site assessment are not held centrally and would be very difficult and time consuming to compile.

NVC surveys – Many sites have had NVC surveys completed for them and this detailed information would provide a very useful resource. This is gathered on a site by site basis and is of variable reliability and age. These data are not held in a central location and accessing the data would be easier in some agencies than others. Sufficient high quality data could potentially be gathered for enough sites to test indicators.

Original NVC data – These detailed and high quality surveys could provide a useful resource although much of it is now quite old and consequently is less useful for relating species composition to current deposition. However, if more recently gathered data could be combined with deposition data from the relevant year this could be a useful resource. Older surveys are less useful because we do not currently have N deposition data going back that far.

Woodland record cards – The woodland record cards give detailed species data including cover for a large number of woodlands across the country. This information is currently in the process of being digitised and would be a potential resource for testing woodland indicators.

ESA monitoring data – Environmentally sensitive area monitoring data for England and Wales are held by ADAS and consists of vegetation data recorded using two main methods. The original method used was based on $4m^2$ quadrats recorded on a diagonal transect across randomly selected enclosures from the earliest designated ESA. A later survey method was based on a fixed plot divided into a contiguous block of nested quadrats. In 1995 and 1996, a large number of the ESA quadrats had soil sampled around their edge allowing a test of indicator robustness based on soil, N deposition and plant species data. These plots covered a range of plant communities. In each quadrat a full list of all vascular plants and bryophytes was made. These data have been used for testing models generated by the Countryside Survey and would be an excellent resource for testing indicators.

ECN data – The Environmental Change Network records data at a range of sites. All vegetation data is recorded as is atmospheric chemistry. Although there are not a large number of sites or habitats, these data are of a very high quality and would be a useful resource for testing indicators.

7.1.1 Example: testing acid grasslands

Data from an independent survey of 20 acid grasslands across the British Isles conducted in 2007 as part of the ESF/NERC project BEGIN can be used to illustrate the validation of ecological indicators of excess nitrogen deposition such as those identified in Chapter 4. All of these indicators are based on 'threshold' values (Table 7.1) for elevated N deposition (see section 6). This validation data concentrated on low and intermediate-N deposition sites (only two sites received >25 kg N ha^{-1} y^{-1}) and so this data set is of only limited use in testing the success of identifying high-N deposition impacts. However, it provides a good demonstration of how national data sets can be used to test indicators.

Table 7.1. Potential indicators of enhanced N deposition and threshold levels identified in section 6.

Indicator	**Level**
Vegetation species richness (per 2 m^2 quadrat)	<10
Forb species richness (per 2 m^2 quadrat)	<4
Forb cover (%)	<5
Grass cover: forb cover (%)	>5
Graminoid cover: forb cover (%)	>5
Hypnum cupressiforme cover (%)	>5

Figures 7.1 to 7.6 show the values for each potential indicator from the 2007 survey (Stevens *et al,* unpublished data) together with the corresponding proposed threshold level.

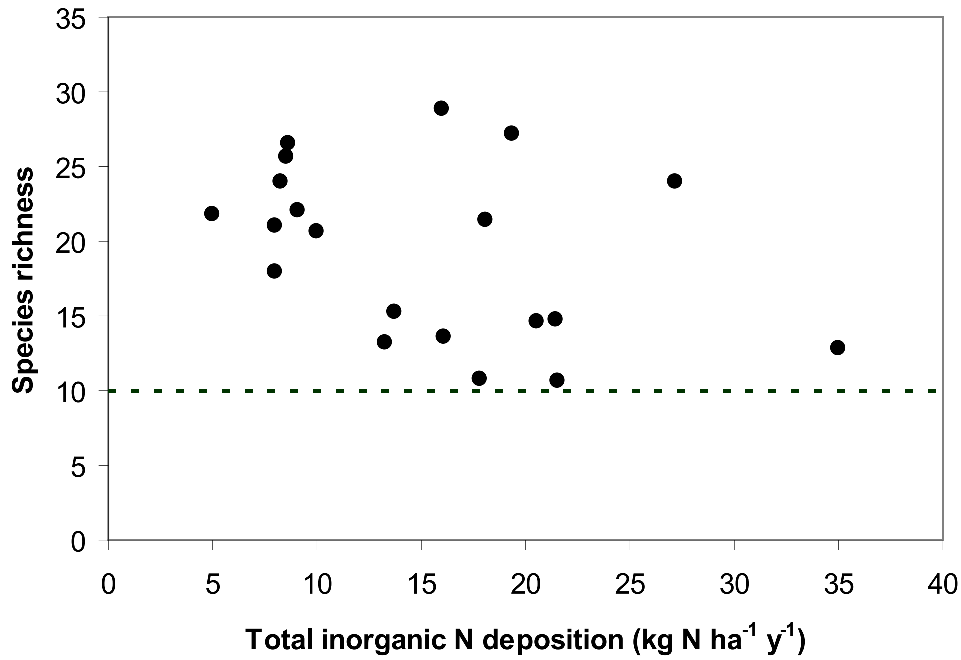

Figure 7.1. Vegetation species richness versus total inorganic N deposition. Proposed indicator threshold of <10 species per 2 m^2 quadrat for elevated N deposition is shown as a dotted line.

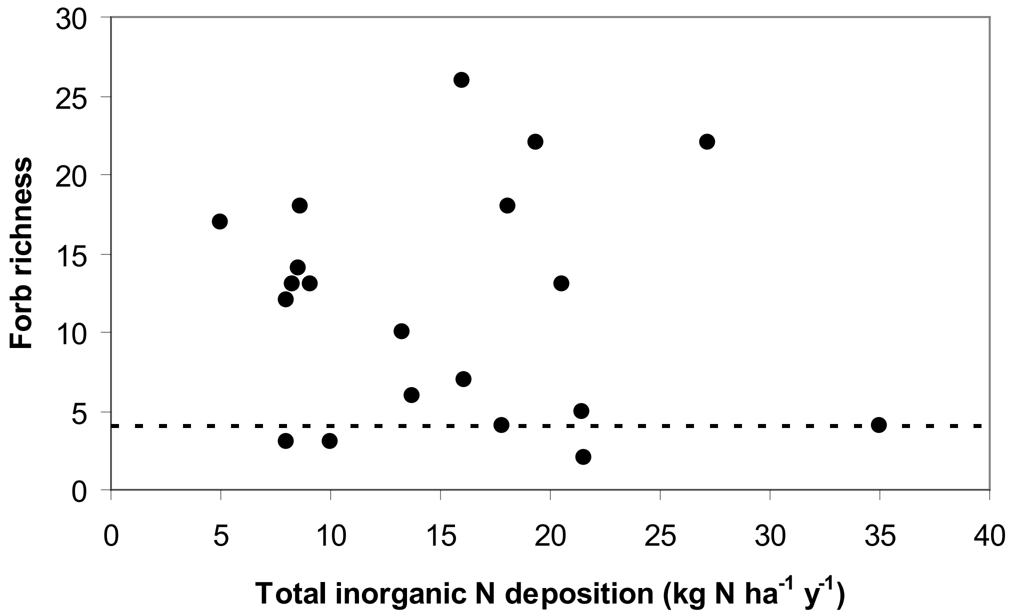

Figure 7.2. Forb richness versus total inorganic N deposition. Proposed indicator threshold of <4 species per 2 m^2 quadrat for elevated N deposition is shown as a dotted line.

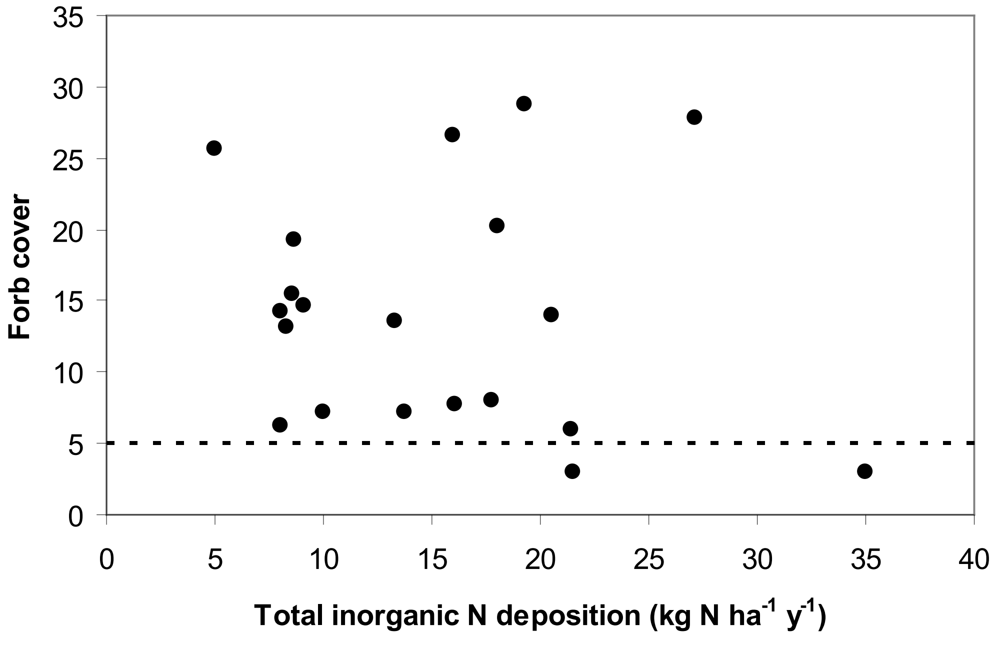

Figure 7.3. Forb cover versus total inorganic N deposition. Proposed indicator threshold of <5% for elevated N deposition is shown as a dotted line.

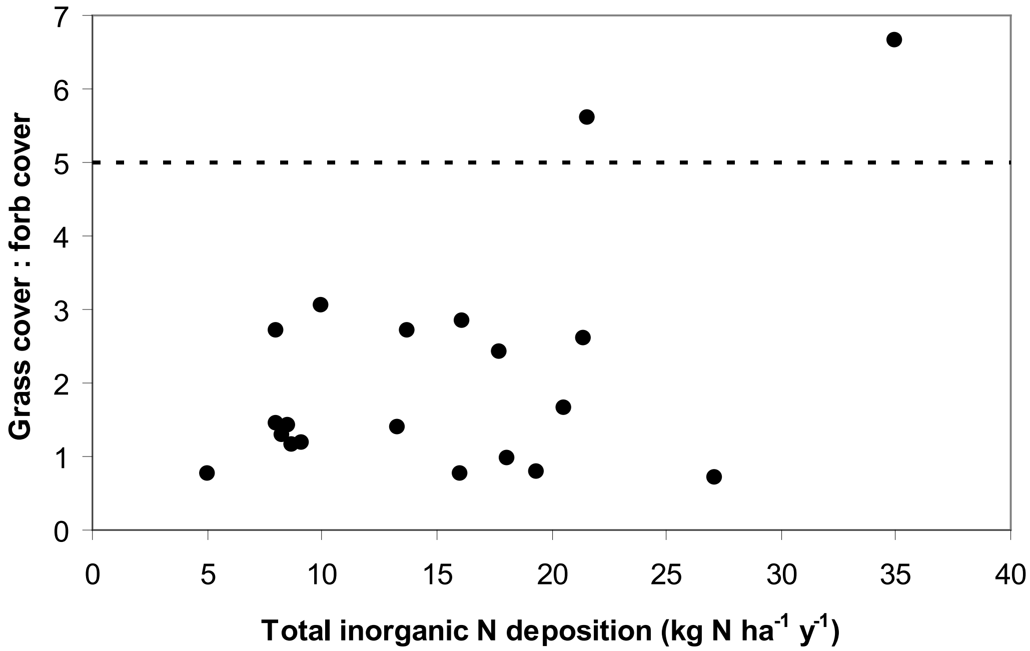

Figure 7.4. Grass: forb ratio versus total inorganic N deposition. Proposed indicator threshold of >5% for elevated N deposition is shown as a dotted line.

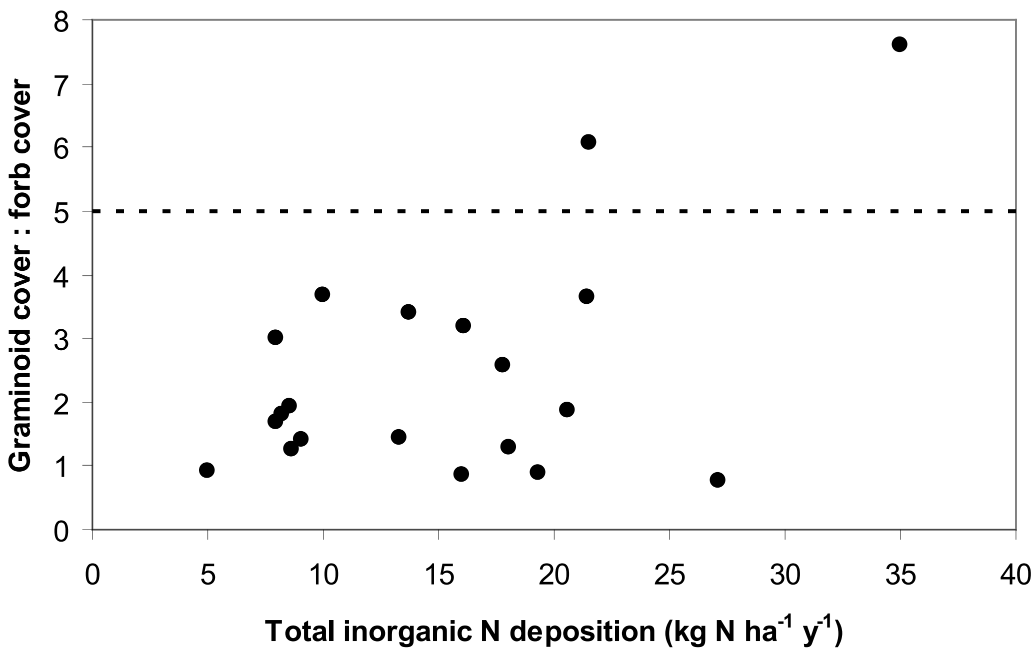

Figure 7.5. Graminoid: forb ratio versus total inorganic N deposition. Proposed indicator threshold of >5% for elevated N deposition is shown as a dotted line.

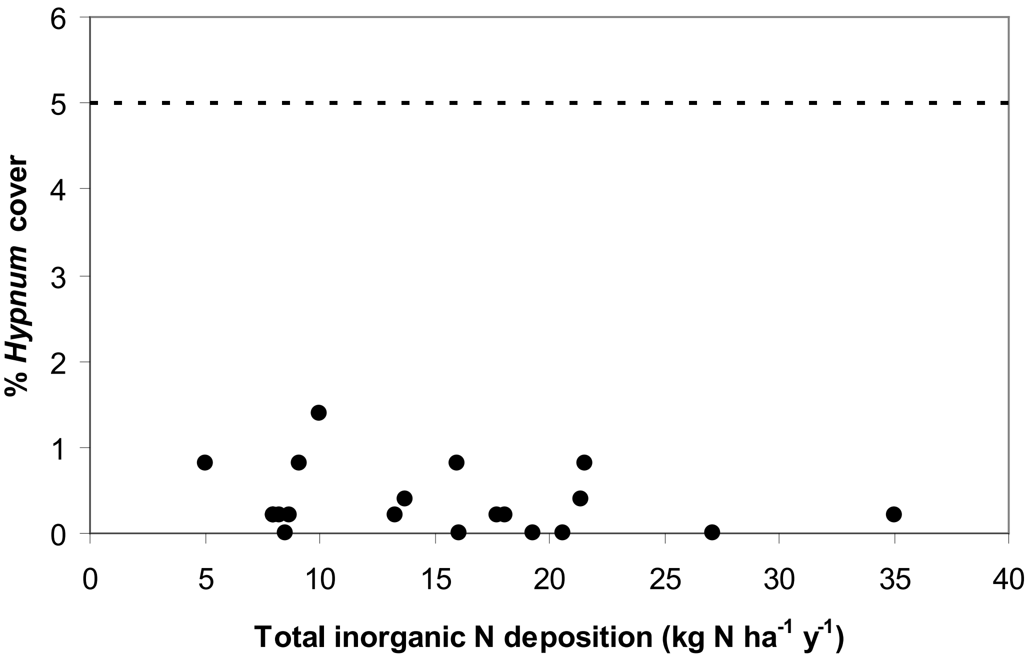

Figure 7.6. *Hypnum cupressiforme* cover versus total inorganic N deposition. Proposed indicator threshold of >5% for elevated N deposition is shown as a dotted line.

With the exception of forb species richness (4 mis-classifications out of 20 sites, or a 20% error rate), all of the indicators successfully categorise the sites, with at most one mis-classification (5% error rate) (Table 7.2). Only forb cover, grass:forb ratio and graminoid: forb ratio, however, identify the high-N site, suggesting that these indicators may be more sensitive to detecting N-deposition impacts.

Table 5.2. Evaluation of indicators.

Indicator	Correct Identification			Separation
	Low-N (/19)	High-N (/2)	Incorrect	
Total species richness	19	0	1	poor
Forb species richness	16	2	4	poor
Forb cover (%)	18	2	1	poor
Grass: forb cover (%)	18	2	1	good
Graminoid: forb cover (%)	18	2	1	good
Hypnum cupressiforme cover (%)	19	0	1	poor

Beyond correct categorisation, a second criterion for a successful indicator is the separation achieved between the low- and high-N groups, to reduce the impact of surveyor error. Since there are only two high-N sites, this is difficult to assess in this data set, however, an estimate can be made by judging the difference between the values of the indicators for the low-N sites and the threshold value. Vegetation species richness, forb species richness, and forb cover all perform poorly on the 'separation' criterion (Table 7.2, Figures 7.1 – 7.6). For example, many of the low-N sites show species richness that is close to 10 (two are ≤11). Thus, a difference between surveyors of only one or two species in a quadrat could easily lead to an unacceptable error level of >15% for this indicator.

Two indicators pass all of the above tests: grass:forb ratio and graminoid: forb ratio. Both correctly categorise 19 out of 20 sites, including the highest N-deposition grassland. In addition, they show good separation between the two categories of high and low-N deposition. Thus, using the (limited) test data and based on the above criteria, the grass:forb or graminoid: forb ratios appear to be the best indicators of nitrogen enrichment in acid grasslands. Since graminoid: forb is less prone to surveyor error, it may be preferable in practice, although grass:forb gives the best separation between the low-N impacted sites and the threshold. Conducting a validation analysis with a larger test data set that encompasses the range of N-deposition values in the UK is the next step toward determining the full usefulness and limitations of these tools in practice.

7.2 Point sources

Point sources provide an interesting potential case study for establishing if N deposition is impacting on a habitat. A point source, such as an intensive animal unit, will have high emissions and deposition in the area around it will be elevated (Pitcairn *et al,* 1998). It is likely that the impacts of N deposition would be detectable in the vegetation and we would expect indicators to reflect this. If a site could be identified which is in close proximity to and downwind of a point pollution source and for which there are already existing data, this could be used to test the indicators. This approach has been used in previous studies (e.g. Pitcairn *et al,* 2004). Some habitats such as these will already have received considerable attention and detailed data may be available (e.g. Moninea bog, NI). However, there are some disadvantages of using a point source to test the methodology. The first of these is that close to a point source N deposition could be much higher than we would expect in the wider environment, so although we would expect an absence of positive indicators, conditions could be so bad that even some negative indicators may not be present. This is due to the distinction between N deposition and other sources of enrichment, we would expect a much stronger change from the use of inorganic fertiliser than we would N deposition because of the quantities and concentrations of N involved. A second problem comes from the type of N deposition. The deposition close to an animal unit will be very strongly dominated by dry deposition of ammonia and so will not be representative of deposition in the UK as a whole. Ammonia and nitrate have different effects on vegetation and the ratio between these can have a significant impact of species occurrence (Kleijn *et al,* 2008).

7.3 Summary

In order to test indicators fully we would recommend the use of existing national data sets. Site level NVC data provides an excellent source of information but because it is not currently held in a central location it is difficult to use. We would strongly recommend that species level data on individual sites of conservation interest is gathered into a central database. ESA monitoring data provides the best currently available source of data for testing the indicators using the approach given above for acid grasslands.

8 Sources of uncertainty in measuring air pollution indicators: spatial and temporal issues

8.1 Overview

In an ideal world, once reliable indicators of air pollution effects are established, these would be measured at high frequency both spatially and over time, thus accounting for variation in site attributes, climate, vegetation stage, regional species pool, management, and all of the other major drivers of vegetation diversity. In addition, differences between surveyors would be minimised by ensuring that all surveyors observed and recorded site conditions similarly (and correctly), used similar criteria for determining the suitable area for sampling, and identified all species correctly and to the same (accurate) level of cover.

In the real world, surveys are limited by time, money, personnel, access, weather, and a host of other factors that mean that measurement of indicators entails numerous compromises. In some cases these sources of variability can be reduced or minimised, in others levels of error can be estimated, in others the best that can be done is simply to be aware of them. This chapter highlights some of the issues raised by variability in time and space that may affect an indicator, and how this variability may be minimised.

8.2 Factors leading to spatial and temporal uncertainty in attribution of pollution levels to indicators

8.2.1 Dynamic changes in communities in response to changing levels of pollutants

Although the results presented in section 6 describe indicators as functions of current levels of N deposition, they actually express the net result of many years of cumulative N deposition (with the exception of communities that do not have a stable substrate), with current N deposition as a reasonable surrogate for the accumulated amount. A century or more of elevated N deposition means there is a high likelihood that major shifts in plant species composition have already taken place in sensitive vegetation types receiving elevated N deposition (Stevens *et al*, 2004, 2006). Therefore, just as the impact of a point application of N in field experiments needs to take into account the impact of cumulative background N deposition, the detection of local impacts of nitrogen deposition needs to account for the expected starting point.

If there is a point source not accounted for by the modelled N deposition, or if N deposition changes significantly (e.g. a major reduction or increase in a point source), the level of the indicator at a site may be out of phase with the level of N-deposition predicted by the indicator equation or threshold value. Such dynamic behaviour could be detected by using the current modelled N deposition for the 5km square on the site of interest to predict the expected state of the indicator (e.g. graminoid:forb ratio, species richness), and compare this with the actual state. Major changes in other drivers, such as long-term climate change, will also influence the relationships described in section 6. Finally, some species, especially non-vascular plants, may respond more strongly to changes in nitrogen concentration rather than deposition (see section 6). Being more directly linked to atmospheric concentrations of gases and aerosol pollutants, these species would also be expected to respond rapidly to changes in those concentrations.

The issue of dynamics in all areas of pollution impact analysis and abatement is an active one (de Vries *et al*, 2007). As N deposition is expected to gradually decline across the UK (NEGTAP 2000), relationships such as those described in section 6 may need to be regularly validated to determine if species richness has rapidly responded to this change, or if it lags behind the change. A thorough understanding of the factors that influence rates of species change under changing levels of drivers such as climate and pollution is necessary to fully address these issues, but is still lacking.

8.2.2 Environmental variation and recorder error

The guiding principle for designing a scheme to record potential indicators of N deposition is that knowledge of other confounding and interacting factors is acquired and used to influence the location and frequency of measurements. The application of this knowledge can be arranged according to a hierarchy of strength:

Controlling the driving factors – Driving factors can be highly controlled in laboratory or greenhouse experiments. This provides maximum power in signal attribution, but by definition lacks realism when the attribution question applies to non-experimental, designated sites.

Recording the operation of driving factors – If quantitative knowledge is available on the location and severity of drivers, the recording of indicators can be organised to optimise the chances of attributing either spatial or temporal change. This will be achieved by either increasing the crossing and degree of replication along each driver gradient and its length or dividing the gradient into control versus impacted sampling domains. However, the lack of experimental design means that spatial confounding, lack of replication and pseudo-replication can weaken signal attribution even though the observations will be highly realistic (Hurlbert, 2004; Oksanen, 2001).

Awareness of driving factors – Even though unmeasured, an awareness of the drivers operating across a site or site series could still support site managers and specialists in decisions as to the importance of N deposition and guide surveillance sampling of vegetation. However, an absence of quantitative information means that the link between driver and impact will be supported by a weaker evidence base.

In practice, each region, site and vegetation type is likely to bring its own constraints and demands for effective sampling to maximise the chances of signal detection and attribution. The important point is to recognise that a recording protocol that is less quantitative and does not take account of other sources of variation is likely to result in a weaker evidence base.

The chances of attributing observed changes in indicator abundance to N deposition will be greater the more other sources of variability are controlled (Stow *et al,* 1998). These include bias between observers, weather and seasonal impacts on cover estimation as well as real ecological impacts on biomass (see for example Kercher *et al,* 2003; Kirby *et al,* 1986; Nilsson, 1992; Oredsson, 2000; Rich and Woodruff, 1992; West and Hatton, 1990).

Reducing the impact of these sources of environmental and human variability can be achieved by applying simple guidelines:

- Record in the same place at the same time of year by the same person or preferably two people.
- If multiple visits through the year are planned, be aware of the possibility of trampling impacts. Consider randomly sampling locations but stratified by vegetation type rather than repeated visits to exactly the same locations.
- Take care to avoid pseudo-replication. For example, this could happen where the vegetation type sampled nearest to a potential point emission source is different from the vegetation type sampled in a control area further away.
- Presence rather than cover-based response variables will be less prone to observer error and other factors that can influence plant cover, but this may trade off against reduced sensitivity to N deposition.

Clearly, in a heterogeneous world outside a designed experiment, the above level of rigor may not be achieved. The important thing is to try to make recording as optimal and sensitive as possible although the impact of different sample numbers or quadrat sizes could be investigated to make integration into CSM guidance easier. Applying these guidelines in light of the intended use of the evidence base will help judge whether proposed recording is likely to deliver the required level of confidence in the attribution.

8.2.3 Single ‘snapshot’ surveys

Single surveys separated by long periods of time may be unavoidable; however, all of the regression equations used to develop the indicators described in section 6 are also based on only one or two surveys. Thus year-to-year and seasonal variability in the levels of the indicators are also not accounted for in these equations. To minimise error in attributing pollution impacts to levels of an indicator in a single survey, it is then necessary to design the survey to mimic as closely as possible the conditions under which that indicator was developed. Further refinement of indicators will ideally encompass different seasons, years, climatic conditions, *etc.* to improve understanding of the sources of variability to those indicators.

There is some evidence that the indicators for N deposition developed on acid grasslands are fairly robust to year-to-year variability, since data from surveys taken over three different years all fall along the same gradients. However, since each site measurement was conducted by the same person (C. Stevens), variability in many other factors was minimised. An important element to standardise is the judgement of site condition and estimate of management. Section 6.1.3 highlighted that differences in the management stage of *Calluna* can lead to major differences in the level of an indicator such as moss cover. Again, this emphasises that care must be taken to ensure that the test conditions are similar to those under which the indicators were developed. For the same reasons, changes in levels of indicators over time should not be attributed to the impact of changes in pollution levels without investigating the levels of other drivers and the circumstances (e.g. season and surveyor) under which a re-survey was carried out. This emphasises the importance of single surveys being well designed in line with guidance above on maximising gradient lengths, the replication of sampling along them and careful crossing with other driver gradients such as SO_x deposition and climate.

Single surveys should ideally be carried out in the same year by surveyors of equivalent skill and executed with the expectation that the survey could be repeated in the future. The following issues should also be considered when recording and interpreting indicator variables:

- Vegetation change comprises random, cyclic and directional dynamics that reflect seasonal and inter-annual processes. Hence, the data gathered in a single survey could partly reflect the position on such trajectories.
- Disturbed patches will change more quickly after disturbance and then more slowly as time since disturbance increases.
- Frequently disturbed vegetation is more likely to comprise ruderal species with fast regeneration times and rapid growth rates. Such plant strategies are inherently more responsive and can change biomass and abundance more rapidly than slower growing species.
- Conversely, in closed vegetation subject to various stresses such as climatic severity, shortage of nutrients, or shortage or excess of water, plants are often slow-growing perennials inherently less able to accumulate biomass rapidly and to exploit gaps.

Disturbance can also be caused by factors such as flooding, dry weather, natural herbivory, pests and disease or management, all of which may operate on predictable repeated timescales or as much more random perturbations, and that could be strongly represented in single recording of plots or locations. If such disturbance events are distributed reasonably randomly across the sampling gradient then they will add random error. This may reduce the apparent explanatory power of N deposition, but will not add bias. However, if these disturbance effects are synchronous across a gradient or, worse, clustered in one part of the N deposition gradient then they may add a level of bias that could confound spatial correlation with N deposition.

All these factors emphasise the importance of accurate knowledge about the location, severity, frequency and type of potential driver on each site in addition to and including point sources of N emission.

8.3 Special issues related to indicators identified in this report

We have sought to determine the best indicator variables for detecting the potential impact of N deposition, yet these relationships are still typified by a large amount of unexplained variation. While some of this residual variation is inevitably related to unmeasured ecological factors and the low resolution of the modelled deposition estimates, some will be due to sampling error in the surveys that generated the species compositional datasets. In order to maximise the sensitivity of these indicators and avoid any bias that could weaken their value as evidence of N deposition impacts, it is important that each indicator is recorded in the same way as in the original survey and with at least equal if not greater precision.

Table 8.1. Definitions of species groups.

Group	Definition
Species richness	Countryside Survey: all higher plants. Stevens *et al* (2004): all higher plants and mosses.
Grass	*Poaceae* (both studies).
Graminoid	Countryside Survey: *Poaceae* and *Cyperaceae* Stevens *et al* (2004): *Poaceae, Cyperaceae* and *Luzula* spp.
Forb	Dicotyledonous higher plants (both studies).

Good sources for verifying growth forms of higher and lower plants in newly collected data are Hill & Preston (2004; 2007).

Plot size and location

Except for heathland indicator frequency (section 6.1.3), all data were recorded in square 2×2m quadrats. Plots were positioned on a stratified random basis in the Countryside Survey and assignment to habitat type by reference to the species composition and broad habitat mapping of the polygon in which the plots were located. In other regional surveys, plots were located at random within vegetation patches identified as the target vegetation type.

In the heathland analysis, frequency was measured as the presence of individual species in each of five quadrats (0.5m × 0.5m) at every site. Frequency values were therefore categorised as either 0, 20, 40, 60, 80 or 100%. The term 'sum of frequency of *Hylocomium splendens* and *Dicranum scoparium*' was simply the frequency of one species plus the frequency of the other at each location. While some variables are not scale dependant (e.g. cover), others, such as frequency are scale dependant. This needs to be considered in deciding the scale at which to assess indicators for integration into CSM guidelines.

Consistent methods of cover estimation

Cover of plant species is notoriously variable between surveyors and is also prone to considerable seasonal variability as the growing season progresses, whilst bryophytes can even appear to change cover with daily fluctuations in surface wetness and humidity. The imperative is to avoid bias. Random error between surveyors will reduce the sensitivity of the measurements to potential drivers and increase scatter about the regression line but will not alter its slope or intercept. Bias is more problematic because it could affect the apparent direction and strength of relationships. The danger is that if it is not avoided or controlled, users may not be able to separate real ecological relationships from bias-induced relationships. For example, if all low N deposition sites were accidentally recorded early in the year before larger, nutrient-demanding herbs had attained maximum biomass, the grass: forb ratios could be low partly as a reflection of season of survey. If high N deposition sites were all recorded later, the grass:forb ratios could be higher again because of seasonal effects rather than cumulative N deposition. The best guidance for avoiding bias is to be vigilant to the possibility of seasonal or observer effects and take steps to increase replication by gathering data across the growing season or at least by starting in the south or in lowland sites, and recording more northerly or upland sites later in the year. Repeated future surveys should then be carried out at the same time of year as the baseline.

A range of scales exist and have been applied to cover estimation. In Countryside Survey, cover is recorded in 5% bands giving maximum flexibility for aggregation into categories or, more usually, transforming to give a more linear relationship with explanatory variables. Other relevant considerations are whether to allow cover to exceed 100% or not. In all of the surveys used in this study, this is allowed because it acknowledges that canopies are layered.

9 How valid and useful is the approach described?

9.1 Acid grasslands

Within acid grasslands there were few species already used as positive or negative site condition indicators that were potentially suitable for use as indicators of N deposition (section 4.1). For all of the species proposed, evidence was either experimental or from surveys; none of the species had evidence from both sources. Examining the potential for new species to be introduced to CSM as indicators of N deposition did not give encouraging results – analyses showed that although there were a number of species that were correlated with either high or low N deposition, presence or absence of these species was not sufficient to distinguish sites on the basis of N deposition (section 5.2). This was because most of the species occurred across the range, albeit at altered frequency.

Using the cover of individual species was also not a reliable indicator of N deposition (sections 6.1.1 and 7.1.1). The main reason for this is that either positive or negative site condition indicators could be at low levels or absent from a particular site for reasons other than the level of N deposition. The most promising indicators of N deposition were other variables such as species richness and cover. Of the variables investigated the most promising were species richness, forb richness and graminoid:forb ratio (based on % cover) (section 6). Testing of these (section 5) showed that graminoid:forb ratio was the most robust, but assessment of this must be made in the summer in order for the threshold value to be applied (the ratio will vary through the year depending on species phenology). Of these variables, the graminoid:forb ratio is also the easiest to apply and most reliable. Although estimating the relative cover of these groups is not always easy in a species-rich grassland, it would be relatively easy to apply in the current CSM framework, since cover of forbs is already estimated in the CSM guidance for upland acid grasslands. As an indicator of N deposition, this seems to be robust, but there are other things that could be responsible for such changes and this indicator should not be used without assessment of source attribution.

The threshold value for graminoid:forb ratio was assessed from the Stevens (2004) data using an average value from five 2x2 m quadrats. This would be recommended for CSM guidance although with further work, this could be adapted for use on a smaller scale (1x1m) and potentially fewer samples.

Attribute	**Target**	**Method of assessment/Comments**
Impact of nitrogen deposition	Graminoid:forb ratio should be less than 5	Target assessed against visual estimate of % cover for graminoids (grasses, sedges and small rushes, such as *Luzula* spp.) and forb at a $4m^2$ scale. Graminoid cover should then be divided by forb cover. Five estimates should be made spread throughout the site and an average values estimated for the site.

9.2 Bogs

As with acid grasslands, there were few species already used as positive or negative site-condition indicators that were potentially suitable for use as indicators of N deposition (section 4.2). Further research is needed on all of the species identified before they could be confirmed as indicators of site condition resulting from N deposition. Analysis of countryside-survey data showed that seven species were identified as positive site condition indicators of N deposition, although no satisfactory negative site condition indicators were identified. The species identified were *Hylocomium splendens* and smaller forbs such as *Drosera rotundifolia, D. intermedia, Pinguicula vulgaris, Polygala serpyllifolia, Dactylorhiza maculata and Pedicularis sylvatica. Sphagnum* species were also identified as a potential indicator, but the difficulties distinguishing species makes them less suitable as indicators. The presence of these positive indicator species during structured observation would be a good indication of positive site condition. The presence of three species out of the seven positive indicator species on a site would indicate positive site condition with respect to N deposition, although further testing of this is needed to be sure this is set at the correct level. A reduction in the frequency of these species would suggest declining quality.

Assessment of other variables showed that species richness, total vegetation cover, grass:forb ratio, *Vaccinium myrtillus* cover and *Polytrichum commune* cover (in randomly located 2x2m quadrats) all gave an indication of site condition in relation to N deposition. Of these, it was felt that although species richness seemed a good indicator, the data would be too time-consuming and require too much specialist knowledge for incorporation into CSM. Vegetation cover and grass:forb ratio both show relationships with N deposition, but the degree of scatter within the data makes setting meaningful thresholds problematic. The most promising indicators for bogs are percentage cover of *Vaccinium myrtillus* and *Polytrichum commune* where high cover of both is an indicator of higher N deposition. For both of these species, cover over 5% could be considered an indicator of negative site condition. This cover estimate is low and may prove difficult to apply in the field, with further data collection it may be possible to refine it to something easier to use.

Further testing would be needed to determine how robust these indicators were before they could be incorporated into CSM guidance, however both of the indicators suggested could easily be incorporated into current guidance where similar methods of assessment are already in use. As with grasslands, other things could be responsible for such changes and this indicator should not be used without assessment of source attribution.

Attribute	Target	Method of assessment/Comments
Impact of nitrogen deposition	Presence of positive site condition indicator species Less than 5% of vegetation cover should consist of either *Vaccinium myrtillus* or *Polytrichum commune*	The presence of three of the following seven species indicates positive site condition: *Drosera rotundifolia* *D. intermedia* *Pinguicula vulgaris* *Polygala serpyllifolia* *Dactylorhiza maculata* *Pedicularis sylvatica* *Hylocomium splendens* Target assessed against visual estimate of % cover at a $4m^2$ scale. Five estimates should be made spread throughout the site and an average values estimated for the site.

9.3 Dwarf shrub heath

As with other habitats, there were very few species already used as positive or negative site condition indicators that were potentially suitable for use as indicators of N deposition (section 4.3). Further research is needed to confirm whether the species identified would be suitable as indicators. There are also a large number of species in all habitats that are potential indicators, but there is currently no evidence to link them to N deposition. Several potential indicators of N deposition were identified using long-term experimentation and regional survey, these were *Cladonia* species (of which *C. portentosa* is the most easily identified) and *Hylocomium splendens*. Since not all species occur at every monitored site, the collective abundance of a few strong indicators provides a more reliable way of determining the impact of N deposition on a site. The best of these indicators was the combined frequency of *H. splendens* and *Dicranum scoparium*. A combined frequency of less than 0.5 (from five randomly placed 0.5 m x 0.5 m quadrats) indicated higher levels of N deposition.

More extensive surveys are needed over a larger geographical range and in more heathland types, especially lowland heathland, to confirm the suitability of this indicator in addition to testing with other data sets. This would also allow more thorough determination of the most suitable sample size to use. This indicator could be incorporated into CSM guidance and although frequency is not currently used much in the guidance, it is very quick and easy to assess. As in the other habitats investigated, there are other things that could be responsible for such changes and this indicator should not be used without assessment of source attribution.

Attribute	Target	Method of assessment/Comments
Impact of nitrogen deposition	The combined frequency of *Hylocomium splendens* and *Dicranum scoparium* should be more than 0.5	Target assessed against presence or absence in five randomly placed 0.25m^2 areas to give a combined frequency score

9.4 Woodland

There are very few indicator species available for woodlands and none of those currently identified for lichen communities in woodland were suitable for the assessment of N deposition impact. The lack of sub-divisions between woodland types makes assessment of indicators for N deposition more difficult – some species may be suitable as an indicator in one woodland type, but may be absent from other woodland types for reasons other than N deposition.

From literature searches and in particular the extensive woodland survey conducted by Kirby *et al* (2005), five species were identified as potential positive site condition indicators: *Deschampsia flexuosa*, *Agrostis capillaris*, *Holcus lanatus*, *Vaccinium myrtillus* and *Isothecium myosuroides*. Potential negative site condition indicators associated with N deposition included *Poa nemoralis* / *trivialis*, *Galium aparine*, *Allium ursinum*, *Athyrium filix-femina*, *Carex pendula* and *Urtica dioica*. These species may not be suitable in all woodland types. Further survey and data analysis would be needed to determine suitable indicators.

9.5 Attributing N deposition

By answering several key questions (section 6) regarding the current and past management of the site, the presence of N sources and critical load exceedence, signs of nutrient enrichment can be attributed to N deposition with a much greater degree of certainty than would be possible using the indicators alone. Changes in management are a particular concern and may lead to similar changes in vegetation composition to N enrichment by deposition. However, for all of the habitats considered a wide range of management intensities and strategies were encompassed through the large number and variety of surveyed sites so much of this variation is already considered in the analysis. Although these types of questions are not currently incorporated into the CSM assessment, all the information should be easy to determine from a site visit or looking at a management plan. This assessment of N source could be conducted at all sites to determine if indicators of N deposition need to be investigated or at sites where N deposition indicators show nutrient enrichment and is suitable for all habitats types.

9.6 Conclusion

We believe that additional information can be gained from incorporating the suggested indicators for acid grassland, heathland and bogs. It will provide an evidence base for policy regarding the impacts of N deposition and offers advancement from the current situation. As the suggested indicators are similar to those already in use the cost of incorporating them will be minimised. For woodlands this situation is more complicated, the lack of division between woodland habitats for CSM guidance makes it difficult to identify suitable indicators.

Further research and testing is required to be sure that there is a high degree of confidence in the results before incorporating indicators and source attribution questions into guidance. Testing could be carried out using existing data as outlined in section 7 but the disparate nature of many data sets means that this may be costly. The collection of new data may provide an alternative and can be done relatively easily. For other habitats, a combination of evaluation of existing data and the collection of new data is likely to be needed to determine and test new indicators.

CSM can only ever be used to give an indication of N deposition as a cause of negative site condition and for more specific results more detailed study of individual sites is needed (see section 10).

10 Estimating the importance of N deposition by calibration against Countryside Survey and other datasets

10.1 Rationale

The potential for incorporating indicators into CSM that can be used to attribute N deposition means that we would recommend this as the best way to proceed. The existing protocols and infrastructure for CSM provide a good base into which new indicators can be inserted to detect impacts of N deposition. As with any indicators, to assess if N deposition really is the cause of the change further, more detailed investigation of individual sites would be needed.

The evidence brought together in this report highlights habitat types likely to show species compositional change in response to atmospheric N deposition. Results from Stevens *et al* (2004, 2006) and from analysis of Countryside Survey data (Smart *et al,* 2003) show that when the spatial pattern of species richness or indicator presence values are modelled as a function of N deposition estimates representing the 20th century maximum, relatively strong relationships are seen. Conversely, when *temporal change* in mean Ellenberg values and indicator presence for the periods 1978 to 1998 were modelled as a function of the same gradient of maximum N deposition much weaker relationships were seen (Smart *et al,* 2003). The implication is that the impact of a century or more of cumulative N deposition may already be apparent in sensitive plant communities and that the rate and magnitude of these changes are often slow and small yet pervasive (Clark and Tilman, 2008). Two key points are therefore relevant for current site condition monitoring and attribution of change to N deposition. First, that the site may already reflect the chronic impact of long-term N deposition and second, that ongoing changes may well be equally subtle and small in size. Having observed low-level directional changes on a monitored site, the key question is to estimate whether these observed changes in species composition are consistent with ambient cumulative N deposition including inputs from local point sources or consistent with other subtle dynamics including seasonal climatic impacts or recovery from past management.

10.2 Possible approach

10.2.1 Reference stands

We propose a two-tier method of monitoring the impact of N deposition. The incorporation of guidance outlined in section 9 into CSM will allow sites where N deposition is a likely cause of vegetation degradation, but for management recommendations to be made, more detailed analysis needs to be conducted. In the proposed scheme, biogeochemical indicators would be used within a second tier of survey measurements to support observations of botanical species and assemblages. Biogeochemical properties such as soil or vegetation chemistry, however, may require specialist knowledge or laboratory analyses, and are not immediately detectable in the field.

It would be useful to compile a reference set of data from stands of vegetation that are considered not to have been significantly impacted by nitrogen deposition to date, in order that new survey data may be compared against such a reference set to identify whether the surveyed site is outside an expected range and therefore requires further investigation. Some reference data sets could be compiled from existing data, such as phytosociological descriptions and ranges of Ellenberg indicator values. Phytosociologically, a community description derived from a set of "clean" stands may differ from that compiled for the National Vegetation Classification, which did not stratify sites according to pollution load. Any newly collected botanical data could then be compared to the reference set using similarity matrices or simple composite parameters such as grass:forb ratios. A score below a pre-set threshold value could trigger the need for further investigation.

This approach could be extended to biogeochemical indicators by taking samples for analysis from the group of reference stands and compiling guidelines for expected values for variables such as % foliar N, %N in litter, N mineralisation rate and pH of surface soil. As for phytosociological data, if corresponding values obtained from a new site differed from the reference set by a pre-determined amount, a need for further investigation would be flagged.

For terrestrial ecosystems the major detrimental effects of N deposition are:

1. Disruption of the internal nitrogen cycle (as evidenced by changes in processes such as nitrification or decomposition);
2. Nutrient imbalances;
3. Soil acidification and loss of base cations; and
4. Loss of biodiversity. A 'knock-on' consequence of nitrogen saturation is eutrophication of downstream surface waters due to nitrate leaching from N-saturated ecosystems. Various studies, including field manipulations, laboratory experiments, and regional surveys, have identified these impacts in different ecosystems.

A wide range of indicators have been proposed for both the level of N deposition and the impact of reactive nitrogen ('N-enrichment') on terrestrial ecosystems (Sutton *et al,* 2004; Leith *et al,* 2005; Morecroft *et al,* 2005). Suggested N-enrichment indicators include (but are not limited to) foliar %N, foliar N:P ratios, extra-cellular enzymes involved in nutrient metabolism, organic horizon C:N ratio, metabolomics ('metabolic fingerprinting' of leaf biochemistry using infrared spectroscopy; Gidman *et al,* 2006), the concentration of soil solution inorganic N, and the flux of nitrate in runoff or leachate.

Table 10.1 shows a selection of potential biogeochemical indicators of nitrogen deposition across a range of terrestrial habitats that could be used to support plant species bio-indicators. The priority column indicates the most practicable and cost-efficient options.

Table 10.1. Potential biogeochemical indicators of nitrogen enrichment across a range of terrestrial habitats that could be used to support plant species bio-indicators. The priority column indicates the most reliable, practicable and cost-efficient options.

Potential Indicators	Comments	Priority
Vegetation		
Foliar %N	Many examples in field surveys; use of some moss species may be best option.	Yes
Soluble N (e.g. tissue ammonium)	Useful indication of NH_y pollution	Possible
Foliar N:P ratios	Inconsistent – works in some systems	Low
Bryophyte /lichen enzymes	Phosphatase and nitrate reductase are the most likely, but needs more field survey testing.	Possible
Amino acids	Total tissue amino acids, and some specific forms are useful (e.g. arginine), but plant species-dependent. Expensive.	Low
Metabolomics	Still at research level	Possible
Litter		
%N	OK if obvious litter layer available (e.g. upland heath, woodlands)	Yes
KCL extractable NH_4^+,NO_3	Good response (especially NH_4^+) in some surveys, but seasonally highly variable	Low
Enzymes	Found useful in heathlands: e.g. phosphatase, phenol oxidase.	Possible
Soil		
% N	Preferably in surface soils (especially OH horizon).	Yes
C:N	Not consistent because as carbon and nitrogen may change together in the same direction.	Low
KCl-extractable NH_4^+	Good response in some surveys, but seasonally highly variable.	Low
KCl-extractable NO_3^-	Good response in some surveys, but seasonally highly variable. NH_4^+ signal generally stronger than $NO3^-$.	Low
Soil enzymes	Similar to above for litter enzymes.	Low
NO_3^- leaching	Some systems (e.g. forests) may leach nitrate before clear vegetation damage occurs, but some other systems retain accumulated N more strongly (e.g. heaths).	Low
Soil pH Base cations	Appears important in grasslands, but influenced by other factors (e.g. maritime, quarrying),	Possible

Exchangeable Al^{n+}	‘threshold’ levels can indicate low risk of nitrogen saturation.	
Net N mineralization	Variable and seasonally changeable.	Low
N_2O emission	Tends to increase with increasing ecosystem nitrogen status, but difficult to determine representative levels in limited field surveys.	Possible

The difficulties involved in using any of these types of measure as an indicator of response to nitrogen pollution or an indicator of deposition is that all are changeable according to the age of the plant, the stage of development and the time of year. Moreover, some are strongly influenced by other factors such as soil temperature and moisture. Our understanding of the reliability of the response variable as an indicator is often much better in some plant species and soil types than in others. More research is required to broaden the applicability of biogeochemical indicators, particularly to determine their most effective combinations with plant species bio-indicators.

10.2.2 Reference trajectories of change

While reference data from unimpacted vegetation stands can be used to undertake like-with-like comparisons and evaluate the conservation value of monitored changes (see 10.2.1), reference trajectories of change in time can also be used as quantitative ‘rulers’ against which to compare the direction and magnitude of changes over time from a nature reserve. The principle is to establish an expected magnitude of change in an indicator species or variable given a particular level of long-term N deposition. Estimates may originate from large-scale observational datasets, experimental manipulation or from modelling studies. All these sources could be used to assemble fingerprints of N deposition but all would carry uncertainties. Hence the best policy would be to build a consensus of possible reference trajectories from as many sources as possible. Countryside Survey data provide a national-scale yet fine-grained reflection of plant species compositional changes and could be further explored. For example, Figure 10.1 shows the relationship between modelled atmospheric N deposition in 1996 and temporal change in cover-weighted mean Ellenberg N for heath, bog and unimproved grassland between 1990 and 1998. The slope is positive and significant yet the r-squared value is small because of other sources of unexplained variation in the data. Further analysis of countryside survey data would be possible that attempted to define less noisy data subsets and that also included the latest 2007 survey data. The aim would be to reduce the width of the prediction interval for this relationship and also to derive habitat-type specific temporal change versus N deposition relationships where possible. Observed changes on nature reserves could then be compared for consistency with the likely magnitude of change expected given time scale and estimated deposition history based on national-scale relationships. Countryside Survey is also comprehensive enough to record the impact of drivers, such as land-use change, on sensitive vegetation types. For example, the larger yet localised and rarer impacts of ley-establishment and arable cultivation are clearly visible in Figure 10.1 and were significantly different in their magnitude of change from the other residuals about the regression line. Thus the other benefit of re-analysing Countryside Survey data is that the size of observed changes can be compared against the magnitude of change expected to result from these additional drivers as well. Building a more comprehensive consensus dataset of reference trajectories that include a larger number of sensitive vegetation types and other drivers could also be achieved as a result of further work to locate and process outputs from modelling studies and experimental manipulations.

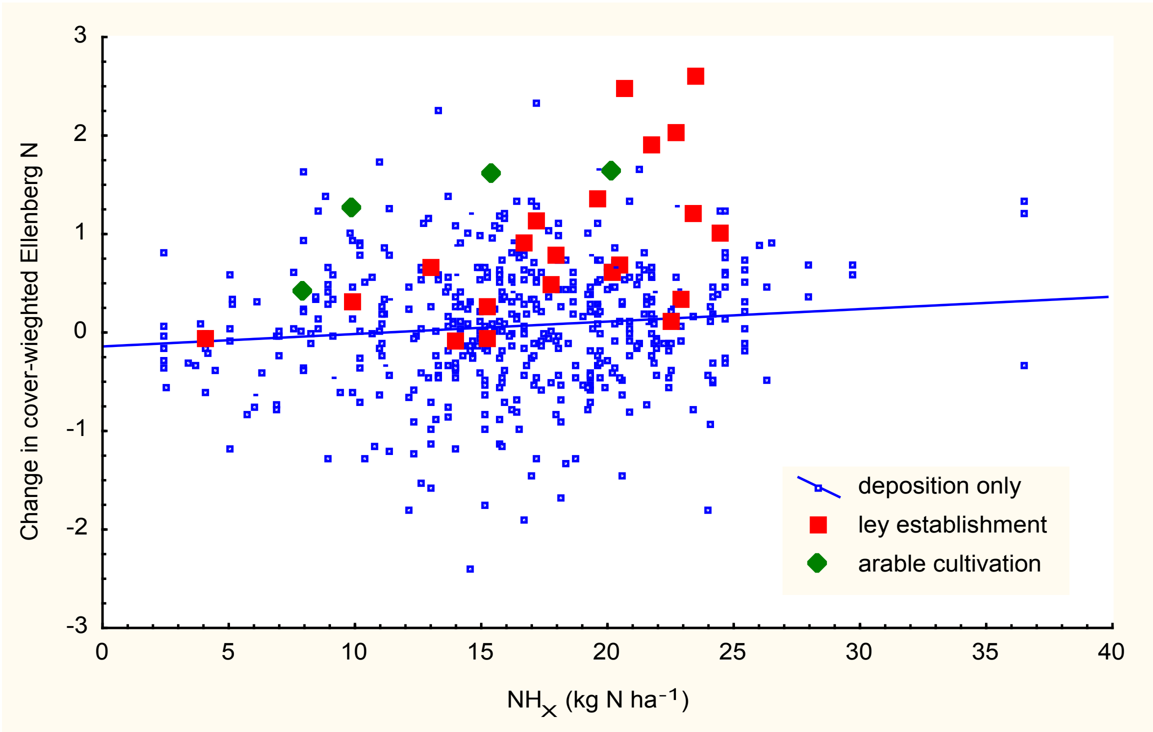

Figure 10.1. Relationship between change in mean cover-weighted Ellenberg N and modelled NHx deposition in 1996 (5 km^2 scale) for CS plots in habitat types with an empirical Critical Load.

10.3 Other habitats

The approach we have outlined is intended to be suitable across the range of terrestrial habitats but indicator species are habitat-specific. The habitats we selected for analysis were amongst those most sensitive to atmospheric N deposition and consequently had received the most research attention. For habitats that have received less research attention, determining indicator species without undertaking new habitat specific surveys may be difficult. We recommend that further survey and analysis of Countryside Survey data is undertaken in other habitats identified as potentially sensitive to N deposition impacts (section 3).

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