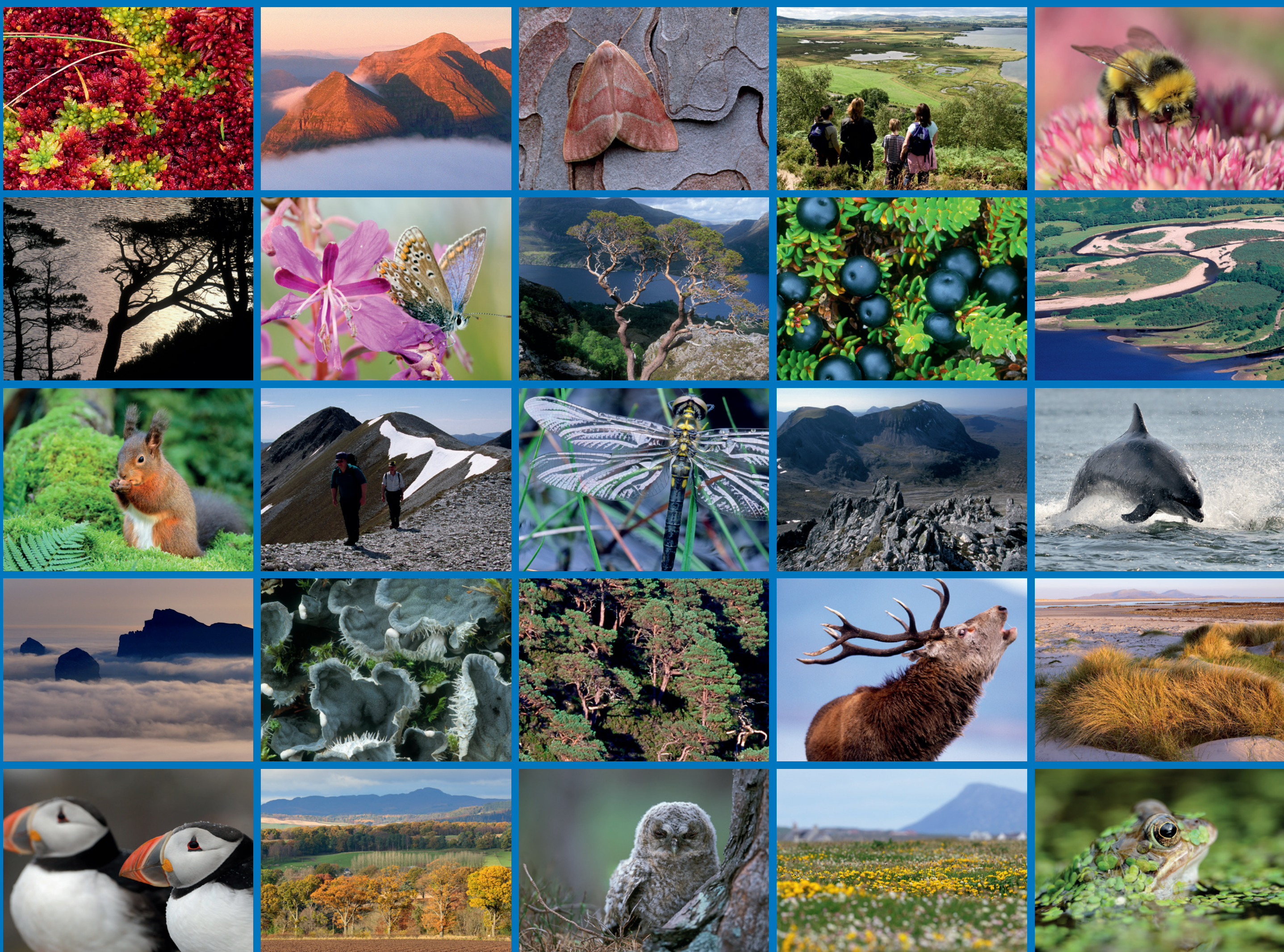
Scottish Natural Heritage
Research Report No. 958

Towards the development of a Nitrogen Deposition Decision Framework for vegetation assessment in Scotland



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RESEARCH REPORT

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Towards the development of a Nitrogen Deposition Decision Framework for vegetation assessment in Scotland

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RESEARCH REPORT

Summary

Towards the development of a Nitrogen Deposition Decision Framework for vegetation assessment in Scotland

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Keywords

Framework; nitrogen deposition; protected areas; quality assurance; site condition monitoring; terrestrial habitats.

Background

Deposition of reactive nitrogen is acknowledged to be one of the greatest threats to terrestrial biodiversity. Deposition of nitrogen has increased greatly following the industrial revolution and, across much of the UK, habitats are exposed to nitrogen deposition in excess of their critical load. Deposition of nitrogen has been associated with reduced species richness of many plant groups, decreased cover of lichens, and increased cover of graminoids. Despite this, Common Standards Monitoring of protected areas does not identify nitrogen deposition as a potential cause of unfavourable habitat condition. In an attempt to provide a mechanism for attributing nitrogen deposition as a threat to, or cause of, unfavourable habitat condition on protected sites, JNCC, SNH and the other UK statutory nature conservation agencies have worked together to develop the Nitrogen Deposition Decision Framework (the Framework). This framework is a means by which nitrogen deposition data and critical loads can be married to the results of Common Standards Monitoring to give an indication of nitrogen impacts on habitat features on protected sites.

The Framework is a potentially valuable tool, in that it provides a clear and logical basis to attribute nitrogen deposition as a threat to, or cause of, unfavourable habitat condition. It can be updated when new evidence becomes available, and incorporates uncertainty in nitrogen deposition data and empirical critical loads. However, SNH has reservations over the Framework approach, due to the substantial gaps in knowledge underlying the Framework outcomes, and the lack of appropriate nitrogen indicators monitored under the current Common Standards Monitoring protocols. In this study, we attempt to address these reservations by objectively comparing Framework outcomes against recorded vegetation change for a range of Scottish habitats.

Main findings

- Analysis of vegetation data from repeat surveys covering 12 widespread Scottish habitats from forests to alpine summits demonstrated significant changes in vegetation composition and diversity over a 40 to 50 year period.
- Comparison of vegetation change metrics with information on key drivers including nitrogen and sulphur deposition, climate and grazing, revealed significant relationships between nitrogen deposition and vegetation change in all habitats.
- Factor 1 scores generated by the Framework predicted a range of likelihood of nitrogen deposition impact from very low to very high. N impacts were predicted to be greatest in alpine summits and snowbeds along with blanket bog, upland acid grassland and acidic oak woods.
- A subset of vegetation change metrics linked to nitrogen deposition and with minimal confounding effects of other drivers was selected for comparison with Factor 1 scores. Contrary to expectations we found that in general, there was no clear difference in vegetation change metrics between Factor 1 score categories, or that the differences did not exhibit a logical trend in impact across the Factor 1 categories.
- Factor 2 scoring was carried out for a subset of calcareous grassland plots. Inclusion of Factor 2 scores increased or decreased the level of threat predicted by the framework for some plots.
- Insufficient Factor 2 scores could be generated to allow the relationships between Framework outcomes and vegetation change to be meaningfully tested.
- We conclude that the current version of the Framework has limited ability to accurately attribute the impacts of nitrogen deposition on protected areas and it requires further development before it can routinely be used as part of Site Condition Monitoring assessments.
- Recommendations are made as to how existing datasets and additional data collection could be used to improve the information underlying the Framework to allow more accurate attribution of nitrogen deposition impacts on the natural heritage.

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Acknowledgements

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1. INTRODUCTION

1.1 Background

Atmospheric pollution by reactive nitrogen (N) affects terrestrial vegetation through direct toxic effects (particularly on lichens, bryophytes, slow-growing and stress-tolerant species), increasing the growth of tall, fast-growing plants, and the acidifying effect of nitrate leaching (Jones et al., 2014). Deposition of sulphur (S) and nitrogen has increased greatly following industrialisation and, although SO_x emissions have been controlled by legislation, N emissions are less well controlled, and N deposition has not shown the same magnitude of declining trend (RoTAP 2012). Semi-natural habitats exceed their atmospheric N deposition critical load ranges across much of their area in the UK (Jones et al., 2014), and N deposition has been associated with reduced richness of many species groups, decreased cover of lichens and increased cover of graminoids (Maskell et al., 2010; Southon et al., 2013; Field et al., 2014). Despite this, information from Common Standards Monitoring (CSM) of protected sites (in Scotland known as site condition monitoring – SCM) does not appear to identify N deposition as a potential cause of unfavourable condition at most sites (Williams 2006; Jones et al., 2014).

In recent years, SNH, JNCC and other conservation agencies have been working together to develop the Nitrogen Deposition Decision Framework (the 'Framework') to provide a mechanism for attributing N deposition as a threat to, or cause of, unfavourable habitat condition on protected sites. The Framework is a means by which national N deposition modelling can be married to the results of CSM to give an indication of N impacts on features on protected sites (Jones et al., 2016a). This has largely been developed to better reflect the likely impacts of N deposition on habitat condition and trends in CSM but will also inform Article 17 reporting, and could have implications for casework.

The Framework incorporates both national (Factor 1 score) and site-based (Factor 2 score) information. Factor 1 produces an exceedance score for a given site and habitat type (JNCC CSM community type). It takes into account the modelled value for N deposition at the site derived from national scale mapping, together with a measure of uncertainty around that deposition value, and the habitat critical load range, and uncertainty around this range. The Factor 1 score alone gives the likelihood, in the absence of site based evidence, that N deposition is impacting on habitat condition. Factor 2 summarises information from CSM assessments and other site-based information relevant to assessment of N deposition impacts. This site-based evidence is interpreted as either providing evidence of N deposition impact (to varying degrees) or evidence of no impact (Table 1a). A final assessment matrix (Table 1a & b) combines the outcomes of Factor 1 and Factor 2 scores, and uses the site based evidence, where available, to modify the outcome based on deposition data and critical loads alone. This results in an overall assessment of whether N deposition is likely to be a threat to or cause of unfavourable habitat condition, either currently and/or in the future. Red and orange outcome categories impact on the outcome of habitat condition assessment, while green and yellow categories imply a threat and high threat of N deposition impacting on habitat condition respectively, but do not alter the habitat condition assessment from CSM. The blue outcome suggests that N deposition is not currently considered a threat to habitat condition.

Table 1. Final assessment matrix used in the Nitrogen Deposition Decision Framework, taken from Jones et al., 2016a. a) Colour coded outcome categories produced by the combination of Factor 1 and Factor 2 scores; b) Explanation of the outcome categories.

a)

Exceedance Score (Factor 1 - theoretical / national evidence)	**Factor 2 score** (site based evidence)							
	Strength of site based evidence that N deposition *is not* causing adverse impacts		No evidence	**Strength of site based evidence that N deposition *is* causing adverse impacts**				
	Moderate	Weak		Very weak	Weak	Moderate	Moderately strong	Strong
Very low								
Low								
Medium - low								
Medium								
Medium - high								
High								
Very High								
No critical load								
No exceedance score		not possible to assess	not possible to assess	not possible to assess	not possible to assess			

b)

Outcome	Description	
Blue - No threat	Most likely impacts on habitat condition	Habitat condition and recovery are not being adversely impacted by N deposition, nor are they currently under threat.
	Site condition categorisation	Condition and trend as assessed by CSM or other means remains unaltered.
	Action	Does not require action to reduce N deposition impacts.
	Future prospects	If current levels of N deposition continue, habitat expected to remain unaffected by N deposition.
Green -Threat	Most likely impacts on habitat condition	Habitat condition and recovery are not currently being adversely impacted by N deposition, but this does represent a low-medium level of threat.
	Site condition categorisation	Condition and trend as assessed by CSM or other means remains unaltered; N deposition recorded as a threat.
	Action	May require additional action to reduce N deposition impacts (remedies); would benefit from deposition reduction at national or site-level.
	Future prospects	If current levels of N deposition continue, habitat condition will remain under threat unless effective remedies to reduce N deposition impacts are put in place. If such remedies are put in place, this will reduce current impact and potentially reduce or eliminate the level of threat.
Yellow - High threat	Most likely impacts on habitat condition	Habitat condition and recovery are being impacted by N deposition – although this is not sufficient to cause unfavourable condition or prevent recovery, it does represent a high level of threat.
	Site condition categorisation	Condition and trend as assessed by CSM or other means remains unaltered; N deposition recorded as a high threat.
	Action	Requires additional action to reduce N deposition impacts (remedies); would benefit from deposition reduction at national or site-level. Country Conservation Bodies may choose to investigate some sites further, for example where Exceedance Score is medium-high and where national and site-based evidence appears in conflict.
	Future prospects	If current levels of deposition continue, habitat condition will remain under high threat unless effective remedies to reduce N deposition impacts are put in place. If such remedies are put in place, this will reduce the current impact and potentially reduce or eliminate the level of threat.
Orange - Not recovering	Most likely impacts on habitat condition	Habitat condition is either: (i) already being adversely impacted by N deposition, such that it is unable to recover/improve (i.e. not recovering/improving); or (ii) if currently favourable, set to become unfavourable in the foreseeable future.
	Site condition categorisation	Condition as assessed by CSM or other means may be favourable or unfavourable, but the trend in condition should be set as not recovering/improving (i.e. no change or declining).
	Action	Requires action to reduce N deposition impacts at national or site-level (remedies); would benefit from deposition reduction at national or site-level. Country Conservation Bodies may choose to investigate some sites further.
	Future prospects	If current levels of N deposition continue, habitat condition will not be able to recover or improve and will become unfavourable in the foreseeable future (unless effective remedies to reduce N deposition impacts are put in place).
Red - Unfavourable no change	Most likely impacts on habitat condition	Habitat condition has already been and will continue to be adversely impacted by N deposition.
	Site condition categorisation	Condition should be set as unfavourable and condition trend should be set as no change (or declining if there is evidence from CSM that it is declining).
	Action	Requires action to reduce N deposition impacts at national or site-level (remedies); would benefit from deposition reduction at national or site level. Country Conservation Bodies may choose to investigate some sites further.
	Future prospects	If current levels of N deposition continue, habitat condition will remain unfavourable and not able to recover (unless effective remedies to reduce N deposition impacts are put in place).

The Framework is a potentially valuable tool, in that it provides a clear and logical basis to attribute atmospheric N deposition as a threat to or cause of unfavourable habitat condition. It can be updated when new evidence becomes available, and incorporates uncertainty in N deposition data and empirical N critical loads. However, SNH has reservations over the limitations and deficiencies of the Framework approach. There are substantial gaps in knowledge of N impacts in many habitats, especially some of the important upland habitats present in Scotland. Out of the 47 CSM habitat types, only 12 have ‘strong’ indicators of N deposition (throughout this report we refer to ‘strong’ or ‘weak’ N indicators as defined in the original JNCC N Framework report, Jones et al., 2016c) recorded under the current CSM monitoring protocol. This could lead to inconsistency across habitats in the way in which N deposition impacts will be reported due to the variability in the type of evidence used in the assessments. Crucially, the CSM assessment process was not designed for detecting N deposition impacts, with the consequence that the majority of CSM targets either do not describe ecosystem components sensitive to N deposition, or are worded such that any impacts cannot be reliably attributed to N. Many CSM attributes which could be relevant to detecting N deposition impacts are also subject to confounding effects of other drivers such as climate or management (in this report we use confounding to mean that change in a CSM attribute/vegetation metric cannot be uniquely attributed to N deposition but may also result from the impacts of other drivers, to be consistent with the original JNCC N Framework reports). As a result of the lack of strong N relevant indicators, Factor 2 scores cannot be generated for the majority of habitats or, where they can be generated, are based on weak evidence. Consequently, the Framework outcomes rely heavily on Factor 1 scores generated from modelled national N deposition data and the incomplete knowledge of habitat N responses represented by critical loads. This goes against the core principle of CSM i.e. that of field data records giving a clear picture of what is happening to a feature on a site.

In this study we attempt to objectively compare the Framework outcomes against recorded vegetation change to assess its ability to predict N deposition impacts.

1.2 Key objectives

This project represents Phase 1 of the validation work and involved the use of existing large-scale Scottish vegetation survey datasets originally assembled by McVean & Ratcliffe (1952-1959) and Birse & Robertson (1958-1987). Repeat surveys have recently been carried out by the James Hutton Institute (Britton et al., 2009; Britton et al., 2017a; Britton et al., 2017b; Mitchell et al., 2017) and the University of Aberdeen (Ross et al., 2010, Ross et al., 2012), and were used to determine vegetation change. These results were compared to the outputs of the Framework, to test whether the N threat categorisation from the Framework correlated with recorded vegetation change.

The key objectives of the project were to:

- Improve understanding of the operational issues surrounding the generation of Factor 1 and 2 scores using the Framework.
- Assess how well the Framework performed at predicting which sites and habitats were most impacted by N deposition.
- Provide recommendations as to what further analysis or data collection could help to improve the detection of N impacts through the CSM process. (These will be considered for a possible Phase 2 project).

1.3 Outcomes

Successful delivery of the project will result in a better picture of the degree to which the results derived from the Framework are reflected in actual vegetation change. This will inform SNH's decisions as to whether resources should be invested in incorporating the Framework protocols into SCM delivery and whether the Framework should be applied retrospectively to existing SCM assessments to better inform Article 17 reporting on the impacts of N on protected areas in Scotland.

2. METHODS

2.1 Vegetation survey data

A long-term re-survey approach was used to assess change in Scottish semi-natural vegetation between two survey periods. Initial vegetation survey data were collected between 1952 and 1959 (McVean & Ratcliffe 1962), and between 1958 and 1987 (Birse & Robertson 1976; Birse 1980; 1984) in surveys designed to describe the plant communities present in Scotland. In a series of re-surveys between 2004 and 2013, 1780 plots were relocated and re-recorded (Ross & Flagmeier 2015). Detailed accounts of survey methodology can be found in Britton et al., 2009, Ross et al., 2010, Ross et al., 2012, Britton et al., 2017a, Britton et al., 2017b and Mitchell et al., 2017). In brief, the unmarked plots were relocated based on grid references and topographic descriptions in the original records. Vegetation composition (higher plants, bryophytes, lichens) was recorded as percentage cover of each species in a plot of the same size as the original. Percentage cover data were then back-transformed to the Domin scale to match the original records. Each plot was allocated to an NVC community type based on the closest matching community for the original record, using the programme TABLEFIT (Hill 1996). For this study, we collated these existing resurvey datasets and determined the distribution of available data across CSM habitat types by cross matching of NVC types to CSM habitat types. The twelve CSM habitat types with the greatest sample sizes, a total of 1409 plots, were selected for further analysis (Table 2, Figure 1).

Table 2. Habitats selected for analysis. The number of samples in each habitat category is shown, together with their mean and range values of 2004-06 total N deposition and the current N critical load range (kg N ha^{-1} y^{-1}). Critical loads are as designated in the JNCC Nitrogen Deposition Decision Framework before adjustment for uncertainty (Jones et al., 2016b).

JNCC CSM Habitat type	Sample size	Mean N deposition	N deposition range	N critical load range
10. Lowland dry acid grasslands	127	10.5	4.6 - 25.6	10-15
12. Lowland meadows and upland hay meadows	66	9.9	4.8 - 20.8	20-30
17. Lowland fens	129	12.4	3.6 - 27.2	10-15 (base poor) 15-30 (base rich) not sensitive (swamps)
19. Acid grassland (upland)	163	14.8	4.0 - 24.1	10-15 (dry) 10-20 (wet)
21. Alpine dwarf-shrub heath	147	11.3	5.4 - 23.8	5-15
23. Alpine summit communities of moss, sedge and three-leaved rush	68	13.1	6.0 - 22.5	5-10
24. Blanket bog and valley bog (upland)	124	10.9	5.3 - 20.5	5-10 (blanket bog) 10-15 (valley bog)
26. Calcareous grassland (upland)	142	12.2	4.6 - 24.1	15-25 (on limestone) 10-15 (not on limestone) 5-10 (calcareous snowbed)
35. Moss, dwarf-herb and grass-dominated snow-bed	66	14.3	5.8 - 20.5	5-10 (without *Salix herbacea*) 5-15 (with *Salix herbacea*)
41. Subalpine dry dwarf-shrub heath	201	11.6	4.8 – 22.2	10-20
45. Wet heath (upland)	62	10.3	4.4 - 19.3	10-20
47d. Acidic oak woodland	114	16.9	6.1 - 29.1	10-15

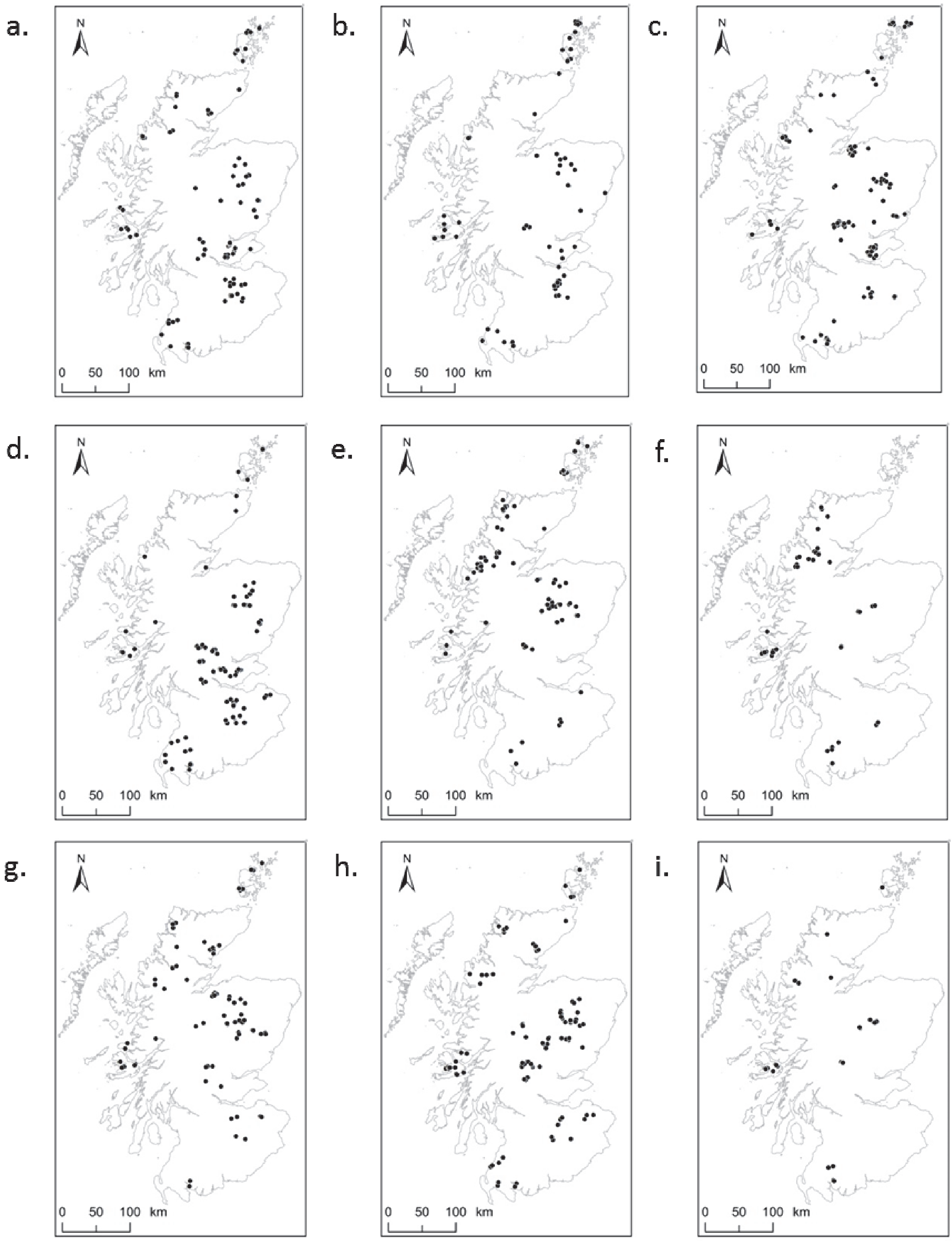


Figure 1. Distribution of Birse and Robertson and McVean and Ratcliffe survey plots used in the analyses for this report. Plots are divided by CSM habitat category; a. 10. Lowland acid grassland; b. 12. Lowland meadow; c. 17. Lowland fen; d. 19. Upland acid grassland; e. 21. Alpine dwarf shrub heath; f. 23. Alpine summit communities; g. 24. Blanket bog; h. 26. Calcareous grassland; i. 35. Snowbed.

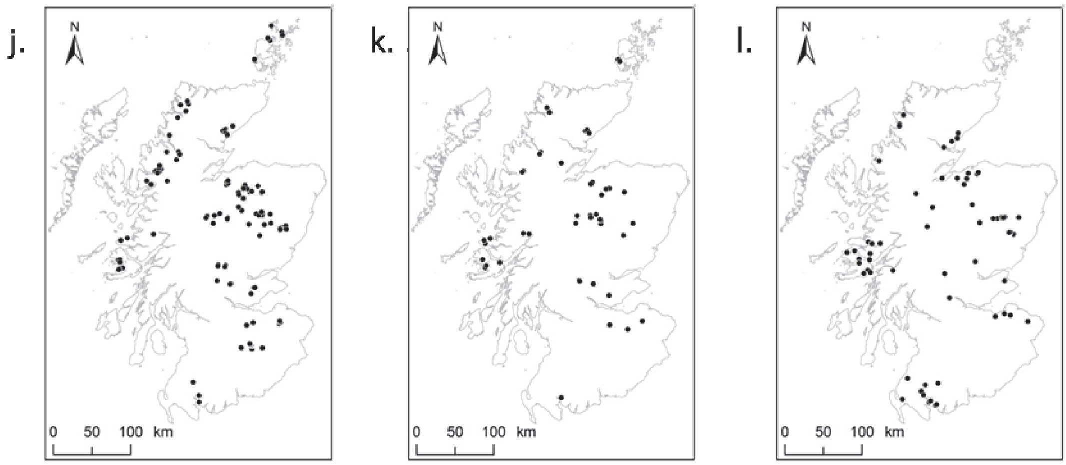


Figure 1 (cont). j. 41. Subalpine dry dwarf shrub heath; k. 45. Upland wet heath; l. 47d. Acidic oak woodland.

2.2 Vegetation metrics and environmental driver data

A range of vegetation metrics commonly associated with N deposition impacts across a range of habitats were selected for use in this study. For each plot, at each time point, we calculated: total species richness, Shannon H diversity index, graminoid - forb cover index (g/(g+f)), vascular - bryophyte cover index (v/(v+b)), cover-weighted mean Ellenberg score for N (Hill et al., 2004, 2007) and the richness and percentage cover of graminoids, forbs and bryophytes. The change between surveys for each of these metrics in each plot was then calculated. The Bray-Curtis dissimilarity index was calculated as a measure of overall change in vegetation composition between surveys, based on the difference in species composition between survey 1 and 2 for each plot.

For each plot location we also collated data describing the key environmental drivers likely to be associated with vegetation change, namely pollution (total N deposition, SOx deposition), climate (mean annual temperature, annual rainfall) and density of grazing animals (cattle, sheep). Wild herbivores (principally deer) will also likely have had a significant impact, particularly on upland semi-natural habitats but suitable data on deer density covering the full geographic range of the plots was not available within the timeframe of this project. Climatic variables were derived from the UKCP09 5 km resolution data for 1941 to 2011 (Perry & Hollis 2005). Mean climate values were calculated for the 10-year period prior to the date of survey for each plot and time point. For the pollution data, cumulative loads of total N and SO_x, were calculated for each plot for the 10-year period prior to each survey and, in the case of total N, also for the year 1900 to the date of survey and for the period between surveys, using 5 km resolution CBED deposition surfaces of the UK for 2004-6 (Smith et al., 2000) and published historical scaling factors (Fowler et al., 2005). Sheep and cattle density data were based on agricultural census data available for 1969 onwards (although not every year) at 2 km x 2 km resolution, supplied by Edinburgh university data library (http://edina.ac.uk/agcensus/). This dataset was extended back to 1941 using published agricultural census data at the county level to interpolate data for each year based on the 2 km gridded distribution in 1969. Mean sheep and cattle densities for each plot were then calculated for the 10 year period prior to each survey date. For grassland habitats, both sheep and cattle data were used; these were combined into a single Livestock Units (LU) stocking rate. For the remaining habitats sheep data only were used, as cattle were unlikely to be present in these habitats.

2.3 Factor 1 scores

Factor 1 and 2 scoring for the selected plots was undertaken by SNH staff. Factor 1 scores ('exceedance scores') were generated using the Framework for a total of 1409 plots covering the 12 selected CSM habitat types (Table 2). Factor 1 scores use national, theoretical (modelled) evidence to assess whether a habitat feature is being affected by N deposition. The following data were used to generate the score:

i. N deposition (kg N ha^{-1} yr^{-1}), usually based on a national model;
ii. Critical load range (accounting for uncertainties in the habitat correspondence (CSM:EUNIS) and new UK evidence).

The N deposition data were put into the Factor 1 Calculation Spreadsheet and the 'exceedance score' for the relevant habitat feature was automatically calculated and recorded. In order to derive the Factor 1 scores, each plot was first assigned to its most appropriate matching CSM habitat category, based on its NVC community type at the time of the initial survey. This information was used in conjunction with the 2004-06 total N deposition rate (kg N ha^{-1} y^{-1}) to look up the appropriate Factor 1 score.

2.4 Factor 2 scores

The Factor 2 score uses site-based evidence to assess whether there are discernible impacts of N deposition on the habitat feature. Evidence is drawn from SCM results and put into a Factor 2 assessment template for the appropriate habitat type (Jones et al., 2016c). These templates include targets that have been identified as strong or weak indicators of N deposition and targets that indicate pressure from other 'confounding factors' (e.g. overgrazing, fertiliser inputs or scrub growth). The results from SCM were input to the appropriate template and the Factor 2 score was automatically calculated. Other site-based evidence may be used to contribute to the Factor 2 assessment, e.g. from site-specific nitrogen studies. For this project, all site-based evidence was drawn from SNH's SCM Database.

Factor 2 scoring was undertaken for a much smaller sample of plots, given that Factor 2 scores can only be generated for habitat types where strong N indicators are recorded as part of SCM targets (Table 3). This limits Factor 2 scoring to 12 of the 47 CSM habitat types, four of which were included in the 12 habitat types selected for analysis in this study. Plots also had to coincide with a designated site with SCM data. This limited the habitats where Factor 2 scoring was possible to four grassland types; lowland acid grasslands, lowland meadows, upland acid grasslands and upland calcareous grasslands. For lowland acid grasslands and lowland meadows, the numbers of plots falling on designated sites were too small for meaningful analysis (<10 plots). Factor 2 scoring was attempted for the upland acid grassland habitat type, but issues with matching of feature types meant that plots could not be linked to suitable SCM attributes and targets and so Factor 2 scores could not be derived. Factor 2 scoring was successfully applied to the upland calcareous grassland habitat type and scores were generated for 32 plots. In this habitat type one strong N indicator with strong confounding factors was available (Table 3). Factor 2 scoring followed the process outlined in the JNCC Nitrogen Deposition Decision Framework, whereby the relevant CSM habitat spreadsheet was selected and the outcomes of SCM monitoring targets entered against the relevant nitrogen indicators to generate a score.

2.5 Data analysis

All data analyses described below were carried out for each of the 12 CSM habitat types separately. In all cases data were checked to ensure that the assumptions of the analysis used (e.g. normality) were met. All analyses except the comparisons of vegetation change metrics and Factor 1 scores were carried out in Genstat v. 18. Analyses of Factor 1 scores were carried out in R (R Core Team 2016). The box-and-whisker plots were produced in the R package *ggplot2* (Wickham 2009).

2.5.1 Change in vegetation metrics between surveys

To develop a picture of vegetation change across the 12 selected CSM habitats over the last ca. 50 years, we first analysed change between surveys for each vegetation change metric. For the continuous variables; Shannon H, Ellenberg N, vascular - bryophyte cover index (v/(v+b)), graminoid - forb cover index (g/(g+f)), graminoid cover, forb cover and bryophyte cover, we used a single sample t-test of the difference between survey 1 and survey 2 (effectively a paired t-test). Bray Curtis distance between vegetation composition at survey 1 and survey 2 was compared against a null hypothesis of no change (Bray Curtis Distance = 0), also using a single sample t-test. For species richness metrics (total richness, richness of graminoids, forbs and bryophytes) generalised linear models (GLM) were used, with a Poisson error term and a log link function. Survey visit and plot identity were included as fixed effects, to produce a model which assessed change between the two survey periods, similar to a paired t-test.

2.5.2 Relationships between vegetation change and environmental drivers

To determine the impact of N deposition (relative to other variables) on long-term vegetation change in Scottish habitats, we then analysed the relationships between the metrics of vegetation change and potential driving variables (pollution, climate, grazing) for each selected habitat. In this analysis we used two measures of the impact of N deposition on habitats; the 10 year cumulative N deposition prior to survey, and the accumulated N deposition between surveys (or cumulative N deposition since 1900 in the case of GLM models of count data). This was done because while the 10 year cumulative N deposition represents the recent average ‘rate’ of deposition and has generally declined slightly between surveys, N is often accumulated in vegetation and soils and so the total N accumulated by ecosystems between the surveys may be a better measure of N impact than the change in deposition rate. It is also possible that different components of the ecosystem are sensitive to different aspects of N deposition, for example, bryophytes and lichens obtain nutrients from rain water and their responses may reflect current deposition, while higher plants access nutrients from the soil and so may be more influenced by nutrient stocks accumulated over the longer term. These two measures of N impact may thus be related to different aspects of ecosystem response.

For all vegetation metrics, a best-subsets regression approach was used to identify those drivers significantly associated with vegetation change. Forward selection, backwards elimination and both forward and backward stepwise regressions were run simultaneously to identify the combination of drivers which best explained change in the vegetation metrics. The optimal models were identified as those with the highest r^2 and lowest Akaike information criterion (AIC) in which all parameters were significant at $P < 0.05$.

Continuously variable metrics (Bray Curtis distance, Shannon H, Ellenberg N, vascular – bryophyte cover index, graminoid – forb cover index, graminoid cover, forb cover, bryophyte cover) were analysed using linear regression models of change in vegetation metrics versus change in the driver variables; 10 year cumulative SO_x deposition, 10 year cumulative N deposition, 10 year mean annual rainfall, 10 year mean temperature and either 10 year mean Livestock Units (grassland habitats) or 10 year mean sheep density (all other habitats) along with cumulative N deposition between survey dates.

Species richness metrics (total, graminoid, forb, bryophyte) were analysed using GLMs with a Poisson error term and a log link function. Survey visit, plot identity and environmental variables were included in the models as fixed effects, with survey visit and plot identity being forced terms. Environmental drivers were; 10 year cumulative SO_x deposition, 10 year cumulative N deposition, Cumulative N deposition since 1900, 10 year mean rainfall, 10 year mean temperature, and either 10 year mean Livestock Units (grassland habitats) or 10 year mean sheep density (all other habitats). This model gives a test of the relationship between driver variables and change between surveys. Following identification of the best model we ran a standard GLM with survey visit, plot identity and the selected drivers as fixed factors. Plot identity and survey visit were fitted first, and a P value was then calculated for the additional fit resulting from the inclusion of the environmental drivers. This ensured that the model P values presented for the GLM models are equivalent to those presented for the linear models used for continuously variable metrics.

For both linear and generalized linear regressions the size and direction of effect of the environmental variables was assessed using the t-values for each parameter in the final models. For all driver analyses, environmental variables were first scaled and standardised to allow for accurate comparison of effect sizes.

2.5.3 Relationships between Factor 1 scores and vegetation change

The best indicator metrics for N deposition impacts for each habitat type (those most closely associated with N deposition and least influenced by other drivers) were selected from the results of the driver analyses for each habitat. The change in the observed values of these selected metrics between surveys was then compared against the Factor 1 scores generated by the Framework. Plots were grouped according to their Factor 1 scores and the magnitude of change in the vegetation metrics between surveys was visualised using box plots and then compared between the Factor 1 score categories using analysis of variance and Tukey multiple comparison tests.

When we found limited correspondence between Factor 1 scores and temporal change in vegetation metrics, we repeated this analysis for the six habitats with the greatest range of Factor 1 scores, using the values of the vegetation metrics at the second survey only. The aim of this preliminary investigation was to test whether the Factor 1 scores better reflected the spatial pattern of N impacts on vegetation composition, rather than temporal change. For this analysis we used vegetation metrics commonly cited as being responsive to N deposition: Shannon H, Ellenberg N, vascular – bryophyte cover index and graminoid cover were used in all habitats; forb cover and graminoid – forb cover index were used in grasslands; and bryophyte cover, lichen cover and graminoid – forb cover index were used in heaths and bogs. As before plots were grouped by their Factor 1 scores and the distribution of the values of the vegetation metrics within each group was visualised using box plots. Significance of differences between Factor 1 categories was then tested for using Analysis of Variance and multiple comparison tests.

Table 3. Summary of strong/ weak scoring of CSM habitat targets as N indicators and for confounding factors (CF) for the 12 selected habitat types. Taken from Jones et al., 2016c.

JNCC CSM habitat types	Number of CSM habitat targets as N indicators and confounding factors (CF)			
	N strong, CF weak	N strong, CF strong	N weak, CF weak	N weak, CF strong
10. Lowland dry acid grasslands	0	1	3	15
12. Lowland meadows and upland hay meadows	0	3	0	13
17. Lowland fens	0	0	4	0
19. Acid grassland (upland)	0	2	0	3
21. Alpine dwarf-shrub heath	0	0	4	1
23. Alpine summit communities of moss, sedge and three-leaved rush	0	0	0	0
24. Blanket bog and valley bog (upland)	0	0	4	0
26. Calcareous grassland (upland)	0	1	0	6
35. Snowbed	0	0	0	0
41. Subalpine dry dwarf-shrub heath	0	0	0	2
45. Wet heath (upland)	0	0	1	1
47d. Acidic oak woodland	0	0	0	0

3. RESULTS

3.1 Change in vegetation metrics between surveys

All 12 of the habitats selected for study had mean Bray-Curtis distance scores significantly greater than zero, demonstrating a significant change in plant community composition over time (Table 4). Of the tested vegetation metrics, four in particular exhibited consistent changes across almost all habitats. These were: decreased Shannon H diversity, which was observed in all habitats except lowland fens, increasing cover of graminoids (significant in 9 out of 12 habitats), decreasing forb cover (significant in 10 out of 12 habitats) and increasing graminoid - forb cover index (significant in 9 out of 12 habitats). Changes in the remaining metrics were more variable between habitats. Mean cover weighted Ellenberg N scores increased in 9 out of 12 habitats, but changes were small and significant increases only occurred in three habitats (there was also one significant decrease). Bryophyte cover, and similarly, the vascular - bryophyte cover index, showed mixed responses. Bryophyte cover declined significantly in four habitats and increased significantly in one. Vascular - bryophyte cover index generally did not change significantly, but declined in two habitats and increased in one. All four species richness change metrics (total species, no. graminoids, no. forbs, no. bryophytes) varied between habitats (Table 5). Total species richness increased significantly in lowland fen, upland acid grassland, alpine dwarf-shrub heath, snowbed and subalpine dry dwarf shrub heath, but did not change significantly in the remaining habitats. Graminoid richness increased significantly in 7 out of 12 habitats. Forb richness generally did not change significantly, but increased significantly in lowland fen, upland acid grassland, alpine dwarf-shrub heath and upland wet heath. Bryophyte richness exhibited mixed changes, with 3 significant increases and 1 significant decline. Notably, alpine dwarf shrub heath was the only habitat type to exhibit a significant increase in all four richness metrics.

3.2 Relationships between vegetation change and environmental drivers

All 12 of the investigated habitats had some significant relationships between N deposition and change in the selected vegetation metrics (Tables 6 & 7). Relationships where a vegetation change metric was uniquely associated with N deposition are illustrated graphically in Annex 1.

Lowland grassland habitats (lowland acid grassland and lowland meadows) showed the least influence of N deposition on vegetation change (Table 6). For lowland acid grassland, overall vegetation change measured by Bray-Curtis distance was related to accumulated N, but the variability explained by the relationship was very small. In lowland meadows, increasing accumulated N was associated with a reduction in Shannon H and an increase in graminoid cover. The relationship with Shannon H was also impacted by change in S deposition. In both habitats, grazing was a more frequent determinant of vegetation change. In the case of species richness metrics (Table 7) none of the metrics was significantly associated with N deposition in lowland acid grassland, while in lowland meadows accumulated N was associated with a reduction in both total and graminoid richness.

Lowland fens had N deposition as a significant factor in the change of several metrics (Tables 6 & 7). Shannon H declined as both 10Y N deposition rate and especially accumulated N increased, however Shannon H was also positively related to temperature. Change in 10Y N and accumulated N were also related to graminoid - forb cover index and vascular - bryophyte cover index respectively in this habitat. Both of these relationships explained a relatively small amount of the total variability. In terms of species richness metrics, total, graminoid and bryophyte richness were all negatively related to accumulated N. However, all of these metrics were also influenced by other drivers, principally S deposition and temperature.

The upland acid grassland habitat type had more relationships with N deposition than its lowland counterpart (Tables 6 & 7). Shannon H declined with increasing 10Y N, though this relationship explained only a small amount of variability. Accumulated N was positively related to forb cover and negatively related to graminoid cover, graminoid - forb cover index and vascular - bryophyte cover index, although in most cases the amount of variability explained was relatively low and there were other drivers in the model. In this habitat both 10Y N deposition and accumulated N affected bryophyte richness, although S deposition was also a significant factor in the model.

The three alpine communities; alpine dwarf shrub heath, alpine summits and snowbeds, exhibited many significant relationships between vegetation change and N deposition (Tables 6 & 7). In alpine dwarf shrub heath all vegetation change metrics except Ellenberg N and graminoid - forb cover index had significant relationships with 10Y N, and in some cases also with accumulated N. The strongest of these relationships was with the Bray-Curtis measure of overall vegetation change, with increasing 10Y N being associated with increasing composition change, although there was also a negative relationship with temperature in the model. In this habitat, increasing 10Y N deposition was associated with a decline in Shannon H and bryophyte cover and an increase in graminoid cover, forb cover and vascular - bryophyte cover index. Although there was some influence of S deposition, there was little influence of climate or grazing on these metrics. Relationships with species richness metrics were not so frequent; total richness and bryophyte richness were negatively related to 10Y N deposition, bryophyte richness was also positively related to rainfall.

Alpine summit communities also had several strong relationships between vegetation change metrics and N deposition metrics (Table 6). N deposition was positively associated with overall vegetation change as measured by Bray-Curtis distance, explaining 28% of the variability in this metric, but there was also a significant negative effect of change in rainfall. 10Y N deposition was also negatively related to Shannon H, cover of forbs, and cover of bryophytes but positively related to cover of graminoids and vascular - bryophyte cover index. Accumulated N was positively associated with Ellenberg N and forb cover. Almost all of these metrics were also influenced by S deposition, climate or grazing. As in the alpine dwarf-shrub heath, 10Y N deposition was negatively related to total richness and bryophyte richness in alpine summit communities. Total richness was also influenced by S deposition.

In snowbed communities overall vegetation change (Bray-Curtis) was positively related to cumulative N deposition and change in S deposition, with a negative effect of grazing. Change in 10Y N was negatively related to Shannon H and positively related to graminoid cover, while cumulative N deposition was positively associated with Ellenberg N and negatively with graminoid - forb cover index. All of these metrics with the exception of Shannon H were also influenced by either S deposition or grazing. As in the other alpine habitats 10Y N deposition was negatively related to total richness and bryophyte richness; both of these relationships were not influenced by other drivers.

Blanket bog and upland wet heath shared similar patterns of response to N deposition (Tables 6 & 7). In both habitats, Bray-Curtis, Shannon H and either bryophyte cover (bogs) or forb cover (wet heath) were significantly related to 10Y N or cumulative N, while the majority of other metrics tested had no significant relationships with the driver variables. In blanket bog, N deposition was the main driver of overall vegetation change (Bray-Curtis) although S deposition was also a significant driver. Shannon diversity declined with increasing 10Y N deposition, though this was somewhat counteracted by the positive effects of grazing. Declining cover of bryophytes in this habitat was solely attributed to 10Y N deposition. Total species richness in blanket bog was negatively related to 10Y N deposition, but was also influenced by rainfall. In upland wet heath cumulative N was the main driver of overall vegetation change along with S deposition. Shannon diversity declined with increasing N deposition in a strong model explaining 28% of the variation without other drivers. N and S deposition jointly explained the variation in forb cover in this habitat. Total richness and bryophyte richness were negatively associated with 10Y N and cumulative N deposition respectively in this habitat, but bryophyte richness was also influenced by S deposition.

Upland calcareous grassland had many strong relationships between vegetation change and N deposition (Tables 6 & 7). Both increased overall vegetation change (Bray-Curtis) and decreased Shannon H were associated uniquely with increasing 10Y N deposition. The relationship with Shannon H was particularly strong, explaining 32% of the total variation. 10Y N deposition was also positively related to the cover of graminoids and bryophytes and negatively to the cover of forbs. There was also a positive relationship between the graminoid - forb cover index and N deposition and a negative relationship with the vascular - bryophyte cover index. All of these relationships were also influenced by either temperature or S deposition; no significant effect of grazing was seen in this habitat. In terms of species richness metrics, both total richness and forb richness were negatively associated with 10Y N deposition in this habitat, while bryophyte richness was negatively associated with cumulative N. The relationship with total richness was not influenced by other drivers while the relationships with forb and bryophyte richness were also impacted by S deposition and temperature.

Subalpine dry heaths also exhibited many strong relationships between N deposition and vegetation change metrics (Tables 6 & 7). 10Y N deposition was positively associated with Bray-Curtis distance, Ellenberg N, graminoid cover and vascular - bryophyte cover index, and negatively associated with Shannon H and bryophyte cover. Of these relationships, the negative relationship between Shannon H and N deposition which explained 15% of the total variability and the positive relationship with vascular - bryophyte cover index which explained only 2% of variability were the only ones not also affected by S deposition, climate or grazing. Total species richness and bryophyte richness in dry heaths were both negatively affected by cumulative N deposition and 10Y N deposition respectively. Both of these parameters were also affected by either temperature, grazing or S deposition.

In acidic oak woodland there were limited significant relationships between drivers and vegetation change, and few relationships with N deposition (Tables 6 & 7). Shannon H was positively related to 10Y N deposition (but also related to S deposition) and Ellenberg N was positively related to cumulative N deposition. Bryophyte richness in this habitat was negatively related to 10Y N deposition, with no other influencing variables.

*Table 4. Changes in vegetation metrics between survey 1 (1950s – 1970s) and survey 2 (2004-2013) for the 12 selected JNCC CSM habitats. Bray Curtis distance is a measure of overall change in vegetation composition, cover values are percentages. Abbreviations: Grams – graminoids, Bryos – bryophytes, g/(g+f) – graminoid - forb cover index, v/(v+b) – vascular - bryophyte cover index. Significance of changes assessed using t-tests is shown thus: *** P < 0.001, ** P < 0.01, * P < 0.05, ns not significant.*

JNCC CSM habitat type	Bray Curtis	Shannon H	Ellenberg N	Cover Grams	Cover Forbs	Cover Bryos	g/(g+f)	v/(v+b)
10. Lowland dry acid grasslands	0.576 ***	-0.165 ***	0.24 ***	2.98 ns	-4.35 **	-0.88 ns	0.044 **	0.008 ns
12. Lowland meadows and upland hay meadows	0.672 ***	-0.242 ***	-0.09 ns	10.35 ***	-10.53 ***	-0.56 ns	0.118 ***	0.006 ns
17. Lowland fens	0.597 ***	0.028 ns	0.04 ns	7.71 ***	-4.67 *	-8.13 **	0.075 **	0.026 ns
19. Acid grassland (upland)	0.508 ***	-0.113 ***	0.08 ns	-2.16 ns	-3.36 ***	4.00 **	0.037 ***	-0.043 ***
21. Alpine dwarf-shrub heath	0.527 ***	-0.438 ***	0.03 ns	8.48 ***	0.16 ns	-3.10 *	-0.023 ns	0.025 ns
23. Alpine summit communities of moss, sedge and three-leaved rush	0.558 ***	-0.464 ***	-0.11 **	4.56 *	-10.03 ***	-1.59 ns	0.044 *	-0.032 ns
24. Blanket bog and valley bog (upland)	0.480 ***	-0.215 ***	0.04 ns	6.10 ***	-1.24 **	-7.21 **	0.037 **	0.039 **
26. Calcareous grassland (upland)	0.578 ***	-0.202 ***	0.08 *	7.67 ***	-10.44 ***	0.75 ns	0.096 ***	0.002 ns
35. Snowbed	0.567 ***	-0.296 ***	-0.01 ns	13.34 ***	-3.59 **	-4.51 *	-0.004 ns	0.024 ns
41. Subalpine dry dwarf-shrub heath	0.463 ***	-0.103 **	0.03 ns	5.30 ***	-1.81 ***	1.35 ns	0.104 ***	-0.025 *
45. Wet heath (upland)	0.566 ***	-0.317 ***	0.01 ns	7.35 **	-0.67 ns	1.58 ns	0.021 ns	-0.013 ns
47d. Acidic oak woodland	0.501 ***	-0.292 ***	0.13 *	0.08 ns	-8.86 ***	2.54 ns	0.068 *	-0.025 ns

*Table 5. Changes in vegetation species richness between survey 1 (1950s – 1970s) and survey 2 (2004-2013) for the 12 selected JNCC CSM habitats. Abbreviations: Grams – graminoids, Bryos – bryophytes. Significance of changes assessed using Generalised Linear Models is indicated thus: *** P < 0.001, ** P < 0.01, * P < 0.05, ns not significant.*

JNCC CSM habitat type	Total no. species	No. Grams	No. Forbs	No. Bryos
10. Lowland dry acid grasslands	0.64 ns	0.53 ns	0.24 ns	-0.25 ns
12. Lowland meadows and upland hay meadows	-1.32 ns	-0.29 ns	-0.76 ns	-0.41 ns
17. Lowland fens	3.25 ***	1.40 ***	1.27 ***	0.31 ns
19. Acid grassland (upland)	1.67 ***	0.59 ***	0.63 ***	0.18 ns
21. Alpine dwarf-shrub heath	1.64 **	0.76 ***	0.53 ***	1.02 ***
23. Alpine summit communities of moss, sedge and three-leaved rush	-0.16 ns	0.40 ns	-0.32 ns	0.40 ns
24. Blanket bog and valley bog (upland)	0.53 ns	0.69 ***	0.00 ns	-0.27 ns
26. Calcareous grassland (upland)	-0.16 ns	1.08 **	-0.63 ns	-0.72 *
35. Snowbed	1.91 *	1.15 ***	0.21 ns	0.58 ns
41. Subalpine dry dwarf-shrub heath	1.79 ***	0.91 ***	0.13 ns	0.51 ***
45. Wet heath (upland)	1.32 ns	0.27 ns	0.48 *	0.92 ***
47d. Acidic oak woodland	1.10 ns	0.39 ns	-0.11 ns	-0.26 ns

Table 6. Significant variables in multiple linear regression of vegetation change metrics versus pollution, climate and grazing variables. Vegetation metrics refer to change in the metric between surveys, with the exception of Bray-Curtis distance which is a measure of vegetation composition change. Potential explanatory variables refer to the change in the 10-year cumulative N or SO_x deposition prior to each survey date (Δ) or the cumulative deposition of pollutants between survey dates (Σ). Rain – 10-year mean annual rainfall (mm), temp – 10-year mean annual temperature (°C), Sheep – 10-year mean stocking density (sheep km^{-2}), LU – Total stocking density (Livestock Units km^{-2}), X – not included as a potential explanatory variable, no model – no significant model could be constructed with the explanatory variables.T-values are shown for each significant variable in each model, along with the adjusted R^2 and P value for the full model (all variables together). Graphs of relationships where vegetation metrics are uniquely associated with N deposition are shown in Annex 1.

JNCC CSM habitat type	Change metric	Δ SOx	Δ N	Σ N	Δ temp	Δ rain	Δ sheep	Δ LU	R^2-adj	P value
10. Lowland acid grassland	Bray Curtis			-2.02			X		2.40	0.045
	Shannon H					2.07	X		2.55	0.040
	Ellenberg N				2.01		X		2.36	0.047
	Cover graminoids						X			no model
	Cover forbs						X	2.06	2.50	0.042
	Cover bryophytes						X	-2.34	3.42	0.021
	g/(g+f)						X			no model
	v/(v+b)						X	2.37	3.53	0.019
12. Lowland meadows	Bray Curtis						X			no model
	Shannon H	-2.24		-3.03			X		10.08	0.013
	Ellenberg N						X	2.53	7.70	0.014
	Cover graminoids			2.06			X		4.77	0.043
	Cover forbs						X			no model
	Cover bryophytes						X	-2.77	9.31	0.007
	g/(g+f)						X			no model
	v/(v+b)						X	2.77	9.31	0.007
17. Lowland fens	Bray Curtis	3.08					X		6.22	0.003
	Shannon H		-3.51	-4.40	2.30		X		22.46	<0.001
	Ellenberg N	2.50					X		3.96	0.014
	Cover graminoids						X			no model
	Cover forbs	2.07					X		2.50	0.040
	Cover bryophytes						X			no model
	g/(g+f)		-2.04				X		2.53	0.043
	v/(v+b)			2.49			X		3.95	0.014

Table 6. Continued.

JNCC CSM habitat type	Change metric	Δ SOx	Δ N	Σ N	Δ temp	Δ rain	Δ sheep	Δ LU	R^2-adj	P value
19. Acid grassland (upland)	Bray Curtis	2.63					X		3.52	0.009
	Shannon H		-2.00				X		1.81	0.048
	Ellenberg N						X			no model
	Cover graminoids			-2.58			X		3.36	0.011
	Cover forbs	3.40		2.79			X	2.39	9.55	<0.001
	Cover bryophytes					3.33	X	-2.17	7.97	<0.001
	g/(g+f)	-3.04		-3.30		-2.08	X		6.61	0.003
	v/(v+b)			-2.14		-3.16	X	2.30	9.96	<0.001
21. Alpine dwarf shrub heath	Bray Curtis		6.14	2.73	-2.80			X	45.48	<0.001
	Shannon H	2.04	-3.90					X	8.78	<0.001
	Ellenberg N	2.62						X	3.85	0.010
	Cover graminoids		5.62					X	17.33	<0.001
	Cover forbs		2.30	-3.19				X	5.57	0.006
	Cover bryophytes	2.70	-5.33				-3.51	X	15.93	<0.001
	g/(g+f)	-2.29						X	3.17	0.024
	v/(v+b)	-3.14	4.88				3.77	X	14.68	<0.001
23. Alpine summits	Bray Curtis		3.95			-2.22		X	28.14	<0.001
	Shannon H	-3.49	-2.79					X	31.62	<0.001
	Ellenberg N			2.56			2.67	X	11.32	0.008
	Cover graminoids		2.91		2.12			X	11.49	0.007
	Cover forbs	2.70	-3.12	3.34				X	11.77	0.012
	Cover bryophytes		-2.23					X	5.62	0.029
	g/(g+f)					4.03		X	18.50	<0.001
	v/(v+b)		3.75				2.90	X	19.16	<0.001

Table 6. Continued.

JNCC CSM habitat type	Change metric	Δ SOx	Δ N	Σ N	Δ temp	Δ rain	Δ sheep	Δ LU	R^2-adj	P value
24. Blanket bog	Bray Curtis	-2.19	5.20					X	17.71	<0.001
	Shannon H		-2.72				2.03	X	8.82	0.001
	Ellenberg N				3.12			X	6.62	0.002
	Cover graminoids						2.28	X	3.28	0.025
	Cover forbs							X		no model
	Cover bryophytes		-3.80					X	9.84	<0.001
	g/(g+f)							X		no model
	v/(v+b)							X		no model
26. Calcareous grassland	Bray Curtis		4.05				X		9.83	<0.001
	Shannon H		-8.19				X		31.89	<0.001
	Ellenberg N				3.14		X		5.92	0.002
	Cover graminoids		3.05		-2.60		X		11.33	<0.001
	Cover forbs	3.59	-5.40	3.03	2.07		X		28.16	<0.001
	Cover bryophytes		2.31	4.04			X		14.42	<0.001
	g/(g+f)		3.66		-3.54		X		17.70	<0.001
	v/(v+b)	3.86	-4.22				X		11.24	<0.001
35. Snowbed	Bray Curtis	3.85		4.43			-2.10	X	26.60	<0.001
	Shannon H		-2.03					X	4.60	0.046
	Ellenberg N	2.84		4.55				X	26.08	<0.001
	Cover graminoids		2.88				3.30	X	29.23	<0.001
	Cover forbs							X		no model
	Cover bryophytes				2.79			X	9.42	0.007
	g/(g+f)	-2.80		-5.52				X	32.91	<0.001
	v/(v+b)	2.65			-2.57			X	17.06	0.001

Table 6. Continued.

JNCC CSM habitat type	Change metric	Δ SOx	Δ N	Σ N	Δ temp	Δ rain	Δ sheep	Δ LU	R^2-adj	P value
41. Subalpine dry heath	Bray Curtis	-4.19	6.41	-3.02	-2.66		3.91	X	28.72	<0.001
	Shannon H		-6.14					X	15.50	<0.001
	Ellenberg N		2.80		-2.45		2.78	X	6.95	<0.001
	Cover graminoids	-4.57	5.76	-4.75				X	13.23	<0.001
	Cover forbs							X		no model
	Cover bryophytes	2.92	-4.03	3.34		2.44		X	7.40	<0.001
	g/(g+f)							X		no model
	v/(v+b)		2.43					X	2.38	0.016
45. Wet heath (upland)	Bray Curtis	3.54		4.25				X	22.66	<0.001
	Shannon H		-4.99					X	28.11	<0.001
	Ellenberg N							X		no model
	Cover graminoids							X		no model
	Cover forbs	2.59	-2.84	3.00				X	9.68	0.031
	Cover bryophytes							X		no model
	g/(g+f)							X		no model
	v/(v+b)							X		no model
47d. Acidic oak woodland	Bray Curtis							X		no model
	Shannon H	-2.72	2.30					X	5.58	0.015
	Ellenberg N			3.65				X	9.82	<0.001
	Cover graminoids							X		no model
	Cover forbs				2.52		-3.51	X	10.36	<0.001
	Cover bryophytes							X		no model
	g/(g+f)							X		no model
	v/(v+b)							X		no model

Table 7. Significant variables in Generalised Linear Models of change in species richness versus change in pollution, climate and grazing. T-values are shown for each significant explanatory variable along with the P value for the full model (all environmental variables), blank cells indicate that a variable was not significant. Potential explanatory variables are: SOx - 10-year cumulative SOx deposition (kg S ha^{-1}), N – 10-year cumulative N deposition (kg N ha^{-1}), ΣN – cumulative N deposition since 1900 (kg N ha^{-1}), Temp – 10-year mean annual temperature (°C), Rain – 10-year mean annual rainfall (mm), Sheep – 10-year mean stocking density (sheep km^{-2}), LU – total stocking density (Livestock Units km^{-2}), X – not included as a potential explanatory variable.

JNCC CSM habitat type	Change metric	SOx	N	Σ N	Temp	Rain	Sheep	LU	P value
10. Lowland acid grassland	Total richness						X		no model
	Graminoid richness						X		no model
	Forb richness						X		no model
	Bryophyte richness				-2.37		X		0.019
12. Lowland meadow	Total richness			-2.63			X		0.011
	Graminoid richness	-2.56		-3.61			X		0.002
	Forb richness						X		no model
	Bryophyte richness						X	-2.08	0.039
17. Lowland fens	Total richness	-2.27		-3.91			X		<0.001
	Graminoid richness			-2.24	2.21		X		0.002
	Forb richness						X		no model
	Bryophyte richness	-3.00		-4.36			X		<0.001
19. Acid grassland (upland)	Total richness						X		no model
	Graminoid richness						X	2.41	0.017
	Forb richness						X	2.56	0.011
	Bryophyte richness	-4.08	2.84	-4.16			X		<0.001
21. Alpine dwarf shrub heath	Total richness		-3.99					X	<0.001
	Graminoid richness							X	no model
	Forb richness					-2.55		X	0.011
	Bryophyte richness		-2.51			2.99		X	<0.001

Table 7. Continued.

JNCC CSM habitat type	Change metric	SOx	N	Σ N	Temp	Rain	Sheep	LU	P value
23. Alpine summits	Total richness	-3.19	-2.41					X	<0.001
	Graminoid richness					2.44		X	0.017
	Forb richness							X	no model
	Bryophyte richness		-3.38					X	0.001
24. Blanket bog	Total richness		-2.90			2.39		X	<0.001
	Graminoid richness				3.45	2.55		X	<0.001
	Forb richness							X	no model
	Bryophyte richness				-2.39			X	0.018
26. Calcareous grassland	Total richness		-6.47				X		<0.001
	Graminoid richness						X		no model
	Forb richness		-4.98		2.21		X		<0.001
	Bryophyte richness	-3.82		-3.26	-2.65		X		<0.001
35. Snowbed	Total richness		-3.40					X	<0.001
	Graminoid richness							X	no model
	Forb richness						-3.19	X	0.002
	Bryophyte richness		-2.73					X	0.008
41. Subalpine dry heath	Total richness	-2.79		-4.79				X	<0.001
	Graminoid richness							X	no model
	Forb richness							X	no model
	Bryophyte richness		-4.40		-2.97		2.18	X	<0.001
45. Wet heath (upland)	Total richness		-3.79					X	<0.001
	Graminoid richness							X	no model
	Forb richness						2.90	X	0.003
	Bryophyte richness	-4.07		-3.67				X	<0.001

Table 7. Continued.

JNCC CSM habitat type	Change metric	SOx	N	Σ N	Temp	Rain	Sheep	LU	P value
47d. Acidic oak woodland	Total richness							X	no model
	Graminoid richness							X	no model
	Forb richness							X	no model
	Bryophyte richness		-4.11					X	<0.001

Table 8. Distribution of Factor 1 scores for the twelve selected CSM habitat types.

JNCC CSM habitat type	Number of plots in each Factor 1 scoring category (% of total in parenthesis)								
	Not sensitive	Very low	Low	Medium low	Medium	Medium High	High	Very high	Total no. plots
10. Lowland dry acid grasslands		19 (15)	37 (29)	5 (4)		51 (40)	15 (12)		127
12. Lowland meadows and upland hay meadows		18 (27)	19 (29)	27 (41)	2 (3)				66
17. Lowland fens	50 (39)	8 (6)	12 (9)	12 (9)	2 (2)	32 (25)	13 (10)		129
19. Acid grassland (upland)		4 (3)	11 (7)	15 (9)		85 (52)	48 (29)		163
21. Alpine dwarf-shrub heath				71 (48)	2 (1)	47 (32)	27 (19)		147
23. Alpine summit communities of moss, sedge and three-leaved rush				1 (2)		19 (28)	41 (60)	7 (10)	68
24. Blanket bog and valley bog (upland)				13 (11)		56 (45)	51 (41)	4 (3)	124
26. Calcareous grassland (upland)		11 (8)	37 (26)			58 (41)	36 (25)		142
35. Snowbed				5 (8)	1 (1)	9 (14)	51 (77)		66
41. Subalpine dry dwarf-shrub heath		20 (10)	57 (28)	57 (28)		59 (30)	8 (4)		201
45. Wet heath (upland)		8 (13)	28 (45)	12 (19)		14 (23)			62
47d. Acidic oak woodland			4 (4)	30 (26)		45 (39)	35 (31)		114

3.3 Results of Factor 1 scoring

The results of the Factor 1 scoring exercise showed a wide spread of Factor 1 scores across most habitats; mainly in the range ‘very low’ to ‘high’ but with a small number of plots in the alpine summits and blanket bog habitats scoring ‘very high’ (Table 8). It was particularly notable that while most habitats had a range of Factor 1 scores above and below the ‘medium’ category, very few plots actually fell into the ‘medium’ category, resulting in a rather bi-modal distribution. To follow this up, we conducted a brief ‘sensitivity analysis’ of the relationships between N deposition rate and Factor 1 score for the 12 studied habitats. In this analysis we simply incremented the N deposition value input to the Factor 1 score spreadsheet in 1 kg N ha^{-1} y^{-1} steps over the range 1 - 40 kg N ha^{-1} y^{-1} (encompassing the current UK deposition range) and recorded the Factor 1 score which was output. Since there is sometimes variability within the CSM categories regarding critical loads of different sub-habitat types (Table 2), where this was the case we selected the most numerous sub-habitat type from each category to investigate. It can be seen from the results (Figure 2) that the range of N deposition associated with each Factor 1 score is not uniform. Assuming that N deposition data are entered as integer values, some Factor 1 scores (particularly ‘medium’ but also ‘medium low’ in some cases) do not occur for some habitats and the Factor 1 score passes directly from ‘low’ to ‘medium-high’. This is particularly the case for those habitats with a narrow critical load range e.g. 5-10 kg N ha^{-1} y^{-1}.

Factor 1 scores were highest in alpine summits and snowbed communities, where 70% and 77% of plots respectively received ‘high’ and ‘very high’ Factor 1 scores. Blanket bog, upland acid grassland and acidic oak wood habitats also received mainly high Factor 1 scores with 89%, 81% and 70% of plots respectively receiving ‘medium-high’ to ‘very high’ scores. Likelihood of N deposition impacts were assessed as least in lowland meadows and upland wet heath where 97% and 77% of plots respectively were assigned Factor 1 scores of ‘very low’ to ‘medium low’. In the remaining habitats there was a wide spread of Factor 1 scores, with a slight bias towards lower scores in subalpine dry heath and lowland fen, and towards higher scores in calcareous grassland. In alpine dwarf shrub heath and lowland acid grassland there was an equal spread of Factor 1 scores either side of ‘medium’.

In the absence of other site-based evidence, Factor 1 scores can be used to generate Framework outcomes (Table 9). The results of the Factor 1 scoring of this set of sample plots suggests that N deposition would be seen as a threat to habitat condition in all habitats across a substantial part of their range, since only those plots scoring ‘very low’ or ‘not sensitive’ for Factor 1 would be judged to be not at risk. Changes in SCM condition assessments (orange and red outcomes) would be triggered for a significant number of plots in most of these habitats; only upland wet heath and lowland meadows had no plots in these categories. Implications for SCM condition assessments would be greatest for alpine summit and snowbed communities where orange and red Framework outcomes comprised 70% and 77% of plots respectively.

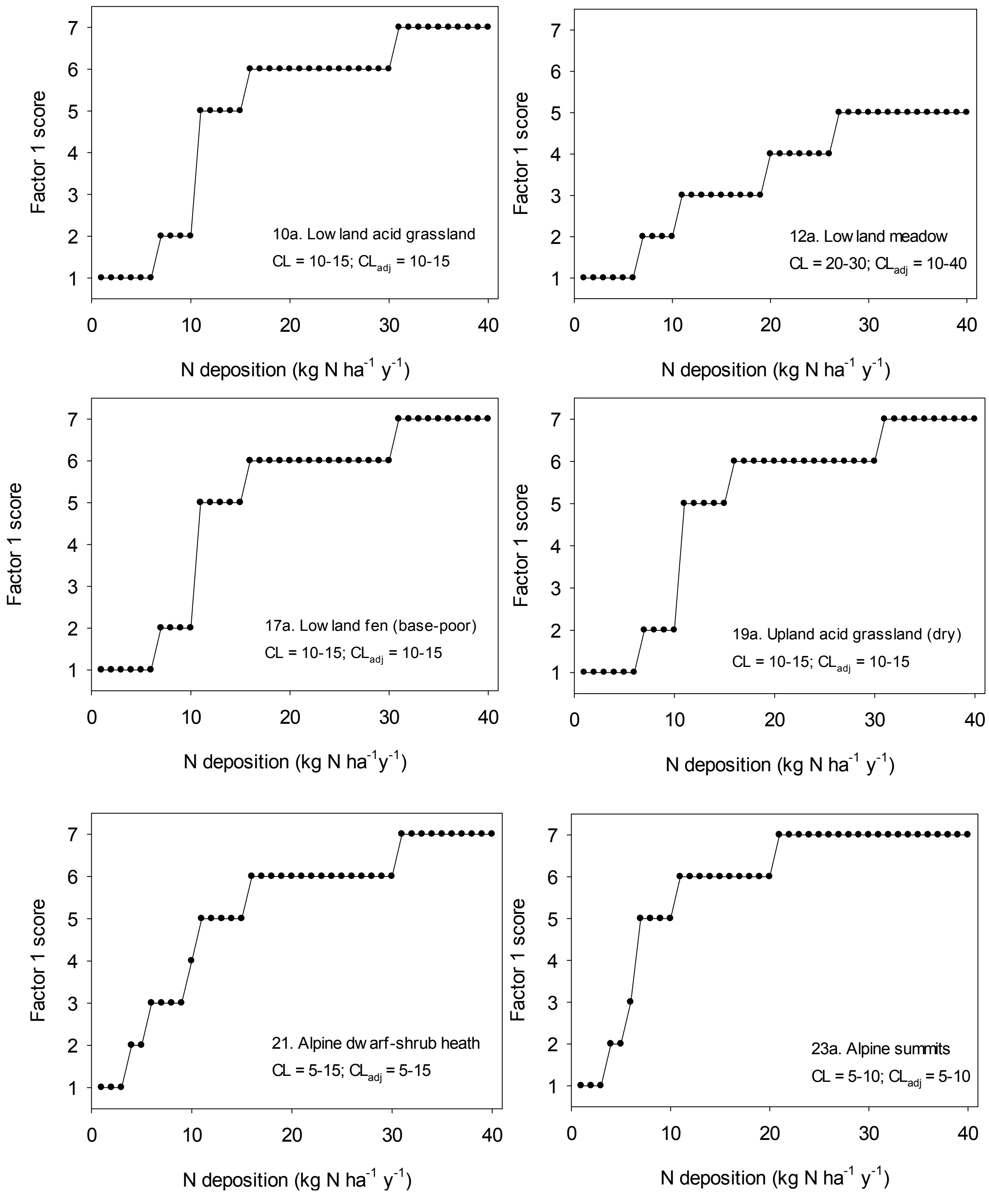


Figure 2. Factor 1 score versus N deposition for the 12 selected habitats used in this study. Factor 1 scores are indicated numerically: 1 – 'very low', 2 – 'low', 3 – 'medium-low', 4 – 'medium', 5 – 'medium-high', 6 – 'high', 7 – 'very high'. The critical load (CL) range (kg N ha^{-1} y^{-1}) and adjusted critical load (CL$_{adj}$) range (accounting for uncertainty) as used in the JNCC N deposition Framework (Jones et al., 2016b) are also indicated for each habitat.

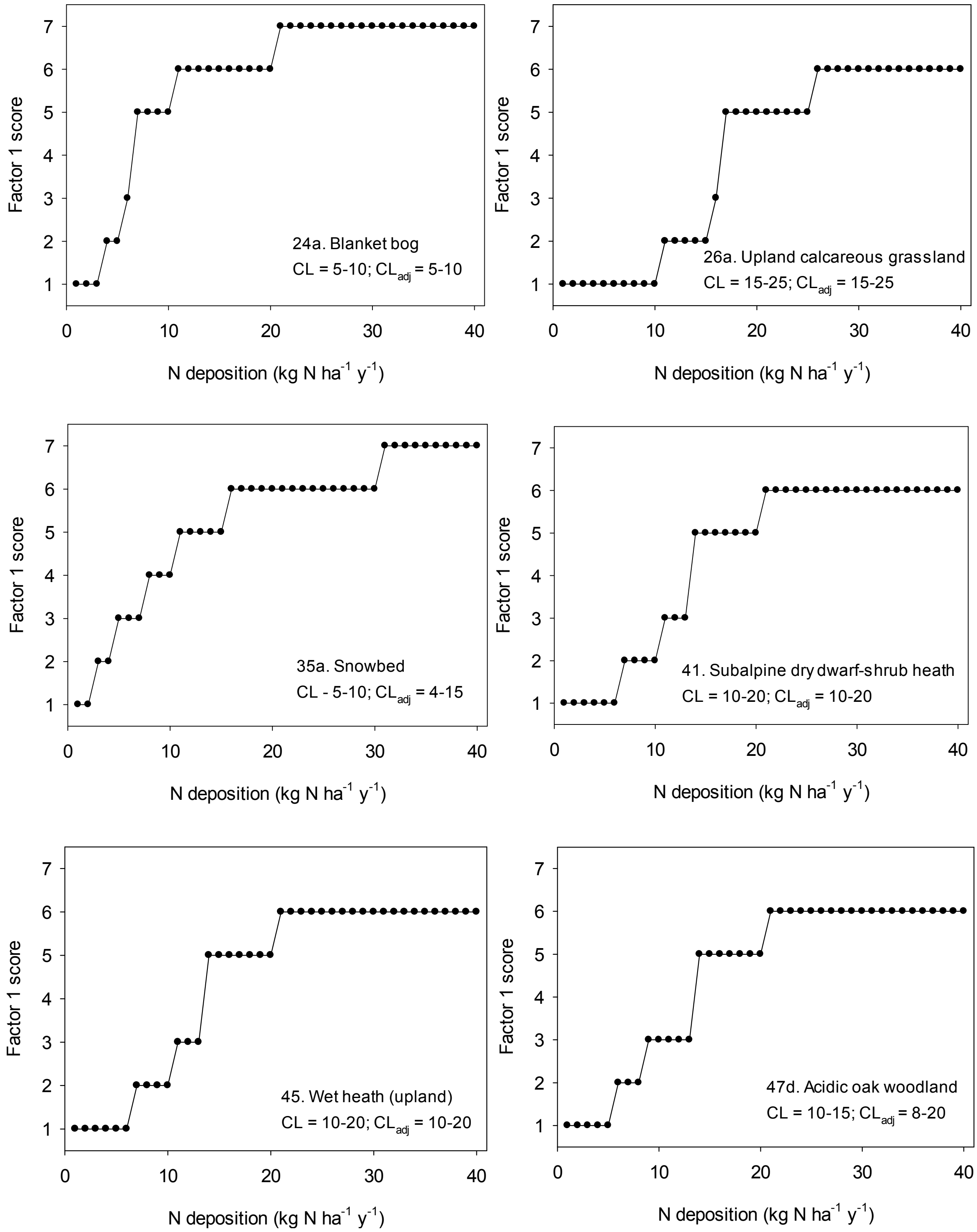


Figure 2. Continued.

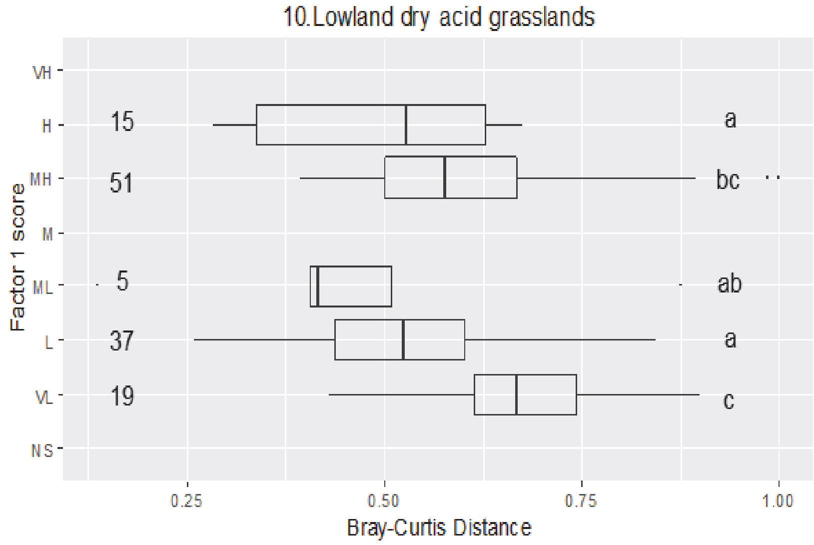
3.4 Relationship between Factor 1 scores and vegetation change

There was a range of at least four Factor 1 score categories in all habitats (Table 8, Figure 3), yet the relationships between the vegetation change metrics and Factor 1 scores were unclear. In general, there was a considerable degree of overlap of vegetation change metrics between the Factor 1 categories, and a lack of an obvious trend. A series of Tukey multiple comparisons tests showed that significant differences between categories only occurred in lowland dry acid grasslands, alpine dwarf-shrub heaths and, to a lesser extent, lowland fens. In lowland dry acid grasslands, the overall pattern of declining Bray-Curtis distance (change in plant community composition) with increasing Factor 1 score is opposite to that which would be expected following nitrogen deposition. Conversely, in alpine dwarf-shrub heath, the lower forb cover in the "high" category is consistent with the known effects of nitrogen, although graminoid cover does not, overall, show the expected increase with Factor 1 score in this habitat. In lowland fens, the increase in the graminoid - forb cover index would be expected with increasing nitrogen deposition; however, this pattern only occurs between the "not sensitive" and "medium-low" categories, as this metric is lower again in the higher Factor 1 categories. A summary of means and standard errors of vegetation change metrics for each Factor 1 score category in the 12 habitats is given in Annex 2.

Since we found only limited correspondence between Factor 1 scores and measures of vegetation change over the last 40-50 years, we followed up our analysis with a brief appraisal of whether Factor 1 scores better reflected the current spatial pattern of vegetation condition (Annex 3). Semi-natural habitats have been exposed to N deposition for a considerable period of time, and it is possible that the spatial pattern of vegetation composition already reflects N deposition, but that ongoing vegetation change is limited. For this analysis we plotted box plots of the range of vegetation metrics for each value of Factor 1, for six habitat types which had a wide range of Factor 1 scores (lowland acid grassland, upland acid grassland, alpine dwarf shrub heath, blanket bog, upland calcareous grassland and subalpine dry dwarf shrub heath). We would expect that sites receiving N deposition below the critical load (Factor 1 of 'very low' or 'low') would differ compared to those receiving N above the critical load (Factor 1 of 'high' or 'very high'). This brief analysis did not account for the effects of confounding variables and a fuller analysis could be done. However, even bearing these caveats in mind, there seemed to be limited significant relationships between vegetation metrics and Factor 1 scores and, where there were significant differences between Factor 1 categories these didn't always follow a logical progression in relation to likely N impacts. In some instances where there were shifts in metric values between Factor 1 categories, the shifts tended to occur between the 'very low' and 'low' categories e.g. for graminoid cover and vascular - bryophyte cover index in lowland acid grassland, for Shannon H and forb cover in upland calcareous grassland and for Shannon H and graminoid - forb cover index in subalpine dry dwarf shrub heath. This may indicate that changes in vegetation composition had occurred below the current critical load value.

Table 9. Nitrogen Deposition Decision Framework outcomes when based on Factor 1 scores in the absence of site based evidence. See Table 1 for detailed description of outcome meanings.

Factor 1 score	Framework outcome
Very low	No threat
Low	Threat
Medium-low	Threat
Medium	High threat
Medium-high	High threat
High	Not recovering
Very high	Unfavourable no change



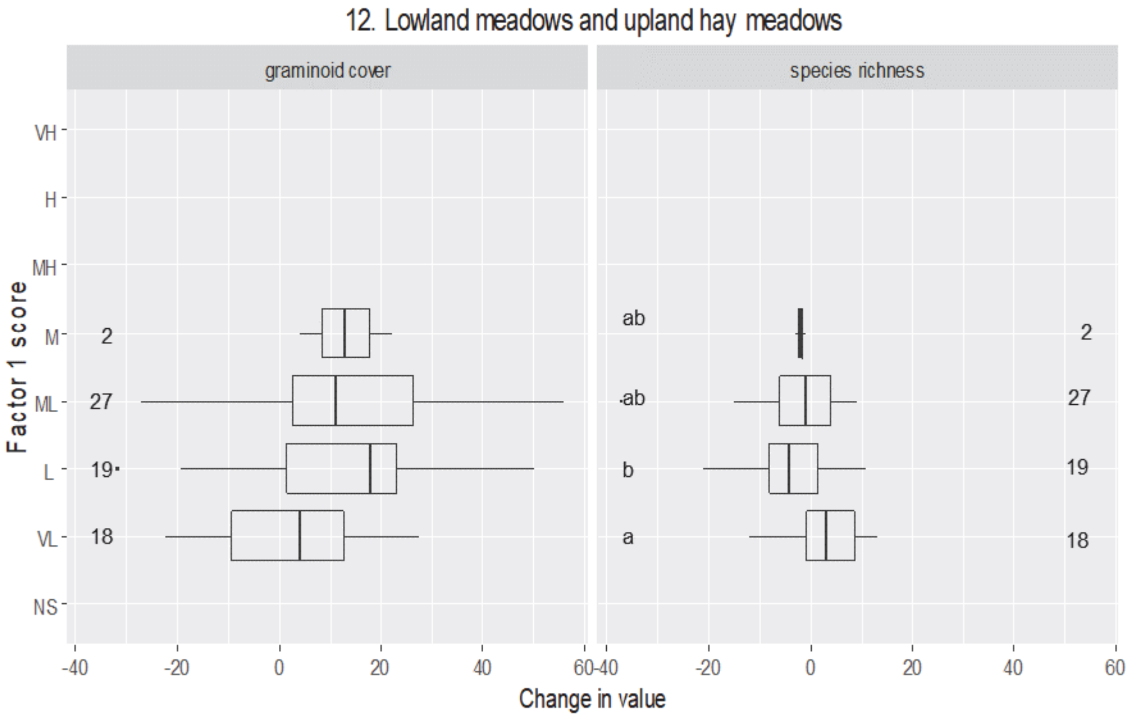
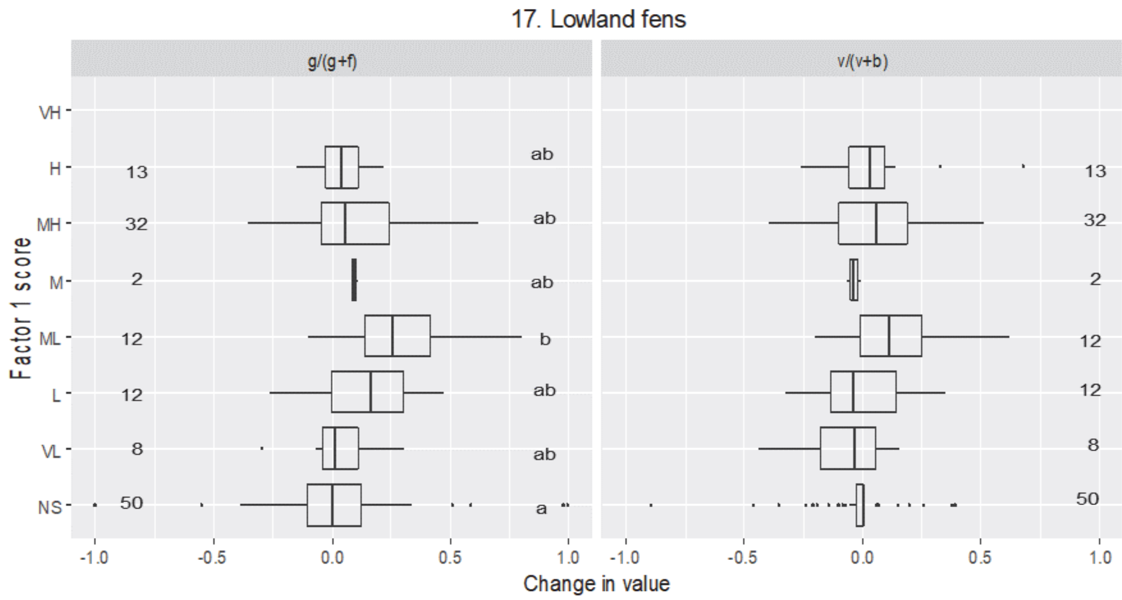
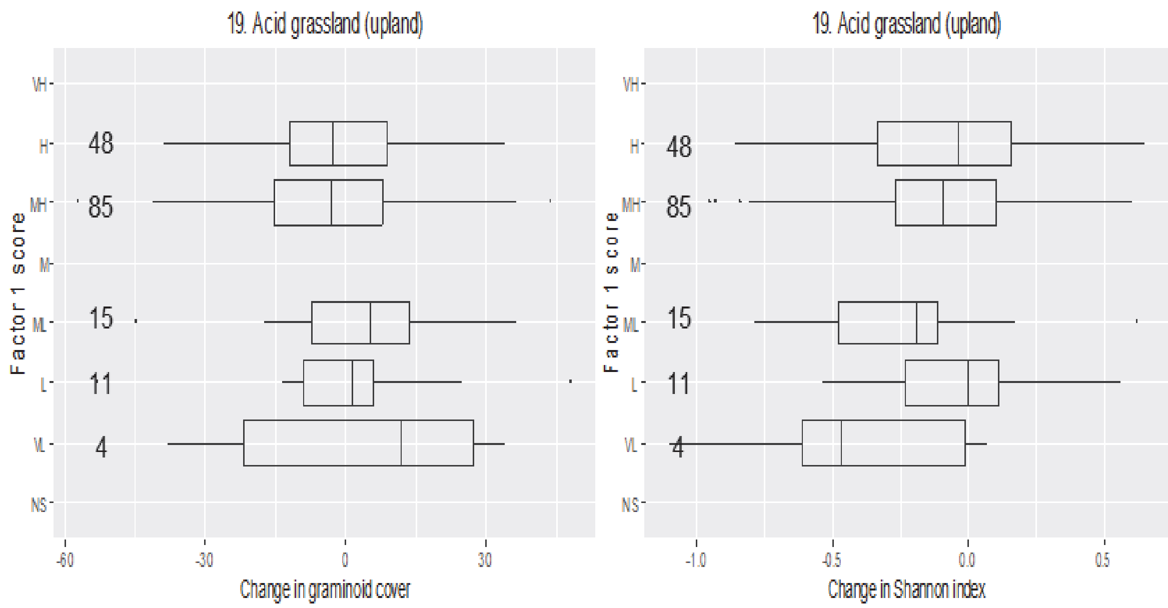


Figure 3. Box plots of the distribution of vegetation N indicator metrics versus Factor 1 score categories. Figures are shown only for those metric/habitat combinations where N deposition was the sole significant driver of change in the vegetation metric (see Tables 5 & 6). Vertical lines within the boxes show, from the left, the lower quartile, the median (thick line) and upper quartile. The horizontal lines to the left and right of the boxes show the lower and upper 'whisker' (10th and 90th centiles) for each Factor 1 category. Dots are outlying values. Numbers on the left of each graph panel show the sample sizes, i.e. number of plots in each Factor 1 category. Letters on the right indicate significant differences between categories; categories not sharing the same letter are significantly different at P < 0.05. If no letters are shown, there was no significant difference between Factor 1 score categories.

Figure 3 continued.





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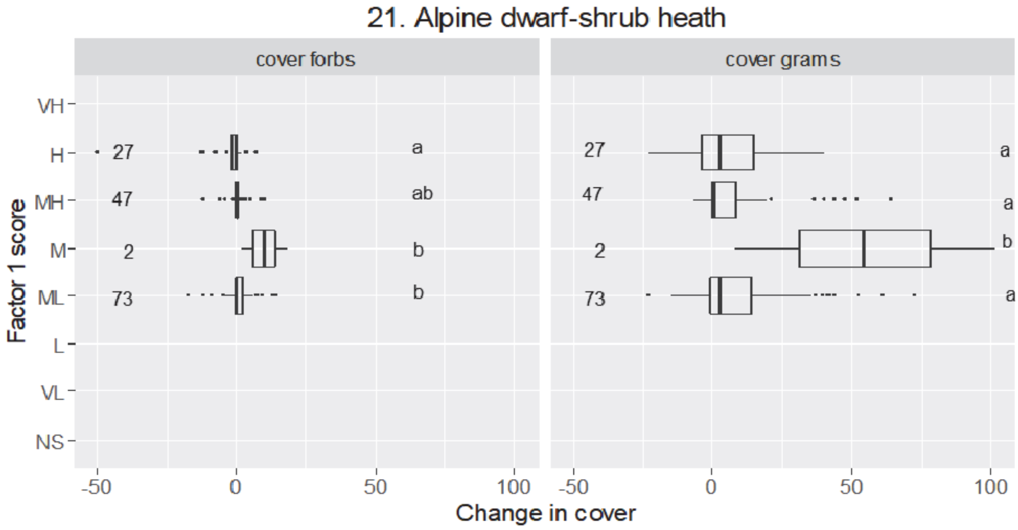

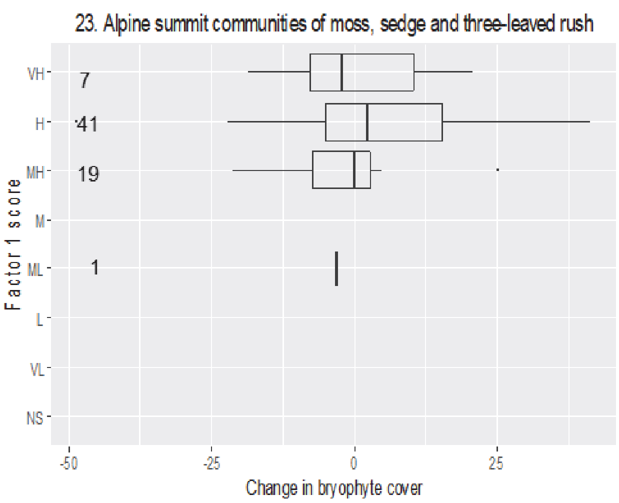

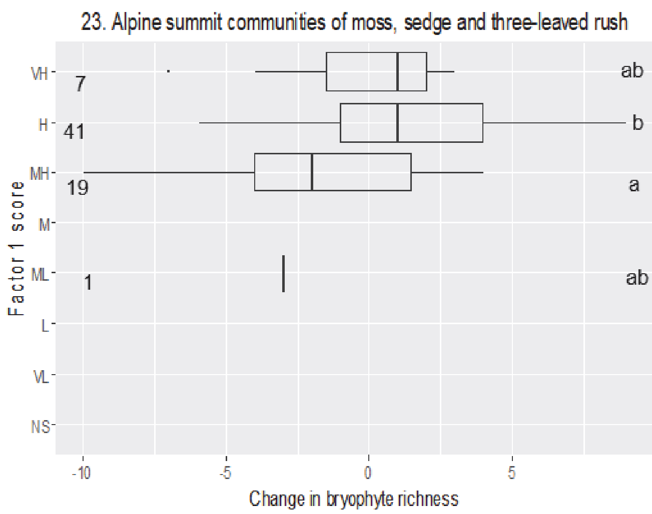

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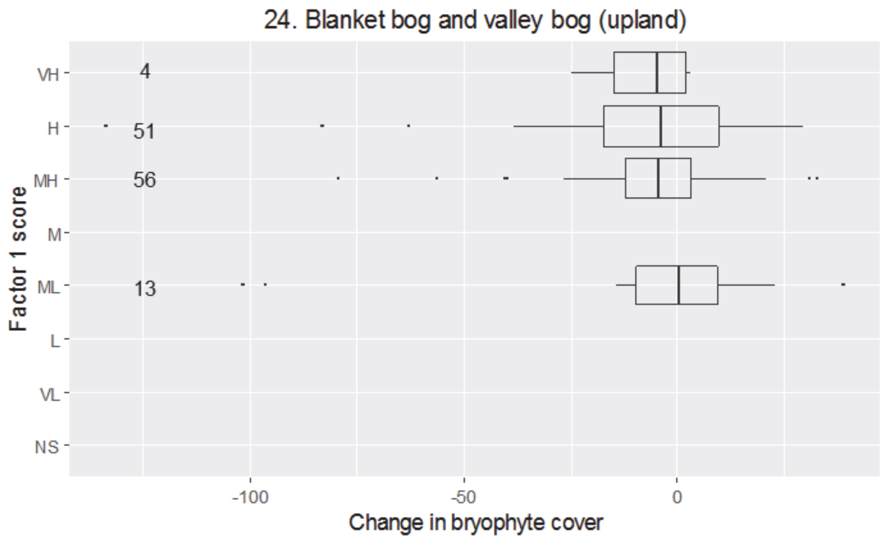

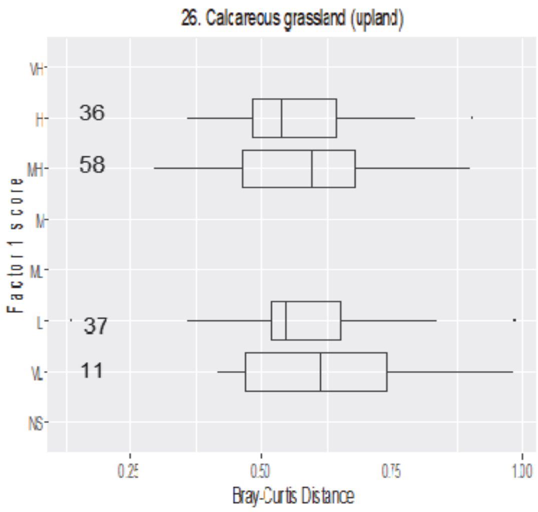

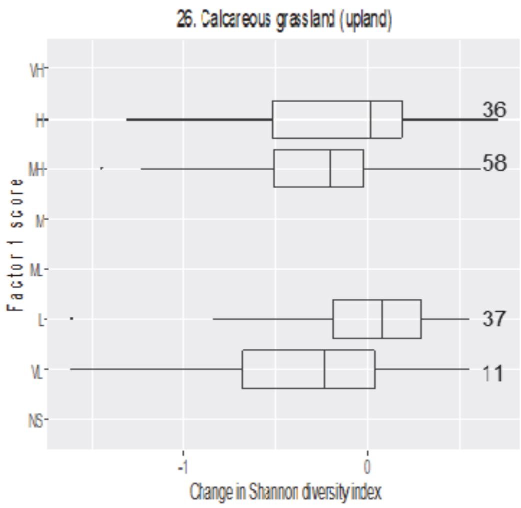

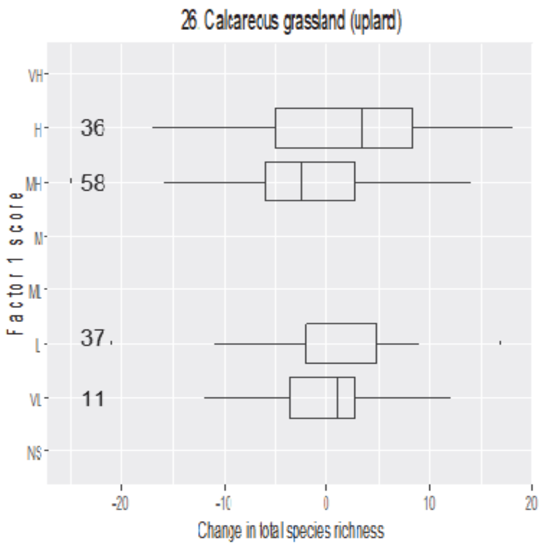

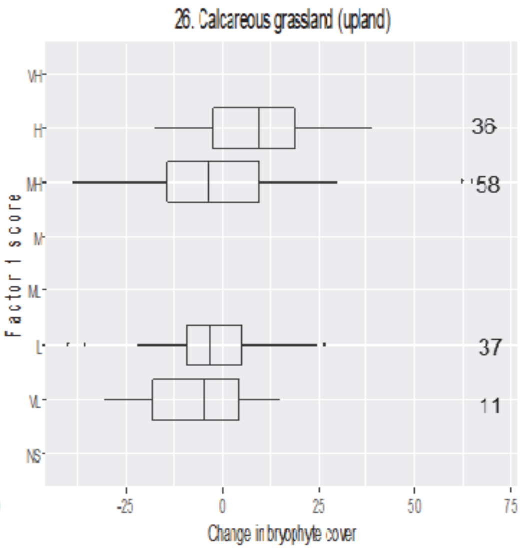

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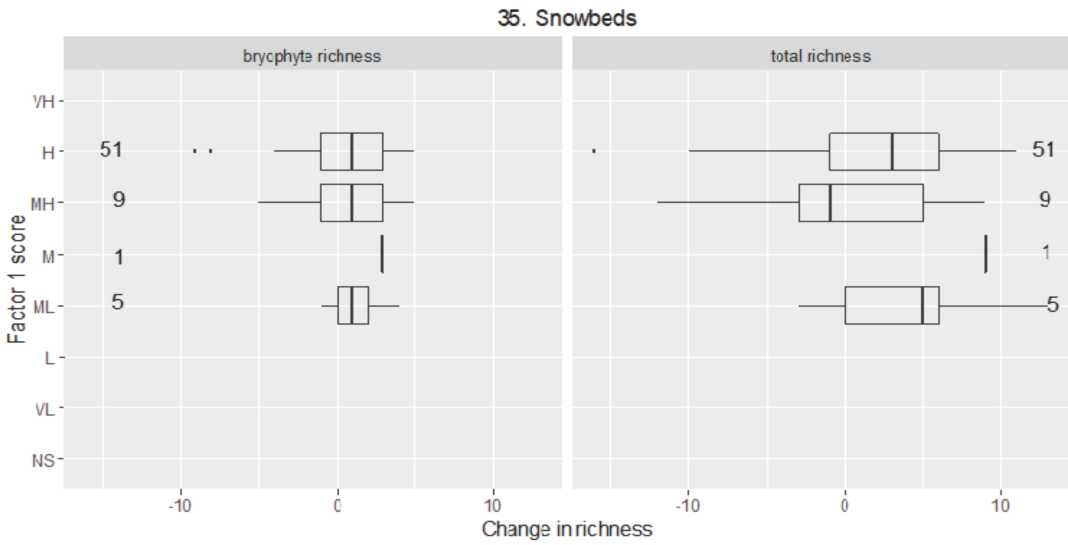

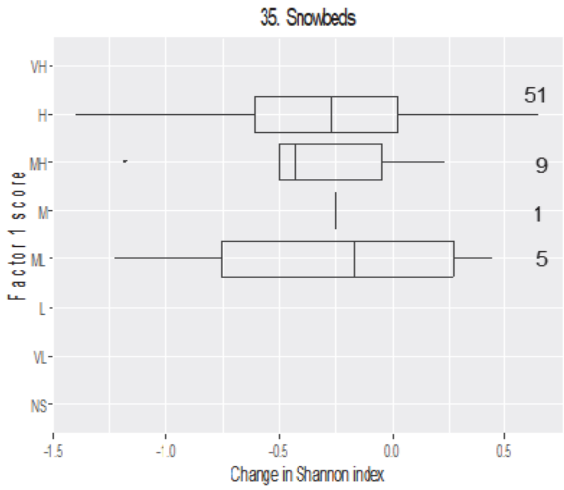

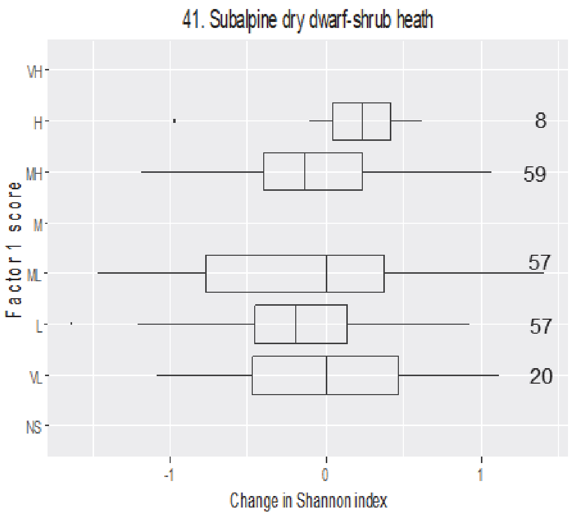

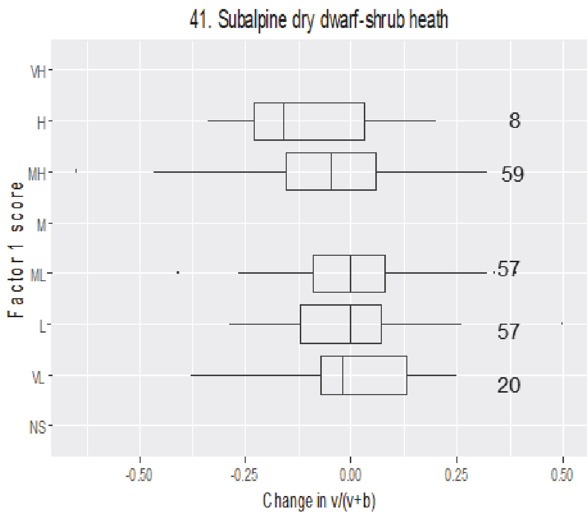

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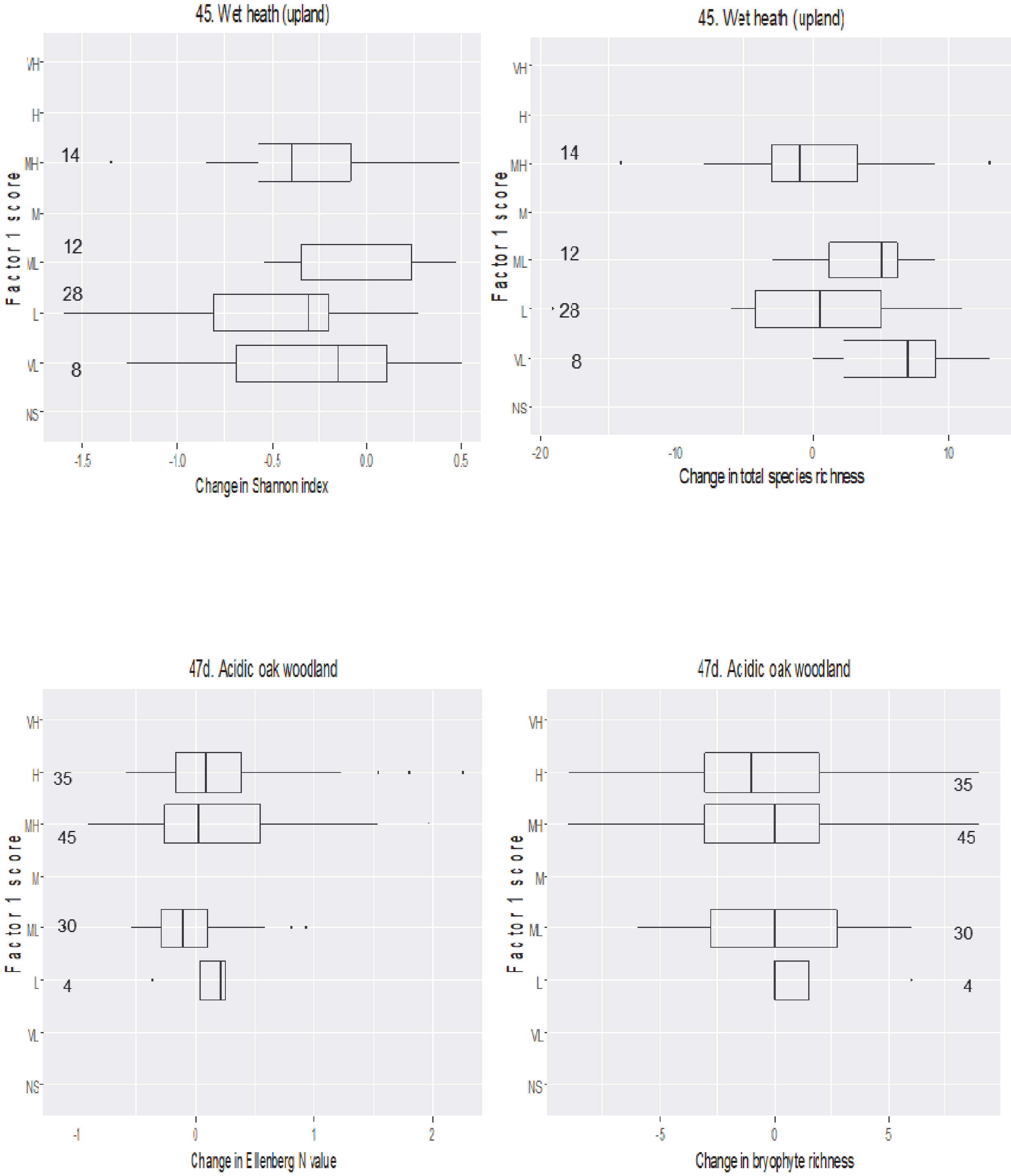

3.5 Results of Factor 2 scoring and overall Framework outcomes

Owing to the limited number of habitats with strong N indicators, Factor 2 scoring was only completed for calcareous grassland (Table 10). Thirty-two plots had SCM data for the appropriate habitat type available to allow Factor 2 scoring to be carried out. One strong N indicator and six weak N indicators were available from SCM data (Table 3). All N indicators were considered to have strong confounding factors. The selected plots had Factor 1 scores of 'low', 'medium-high' and 'high'. Site based evidence from the SCM database gave Factor 2 scores of 'moderate evidence of no impact', 'very weak' evidence of impact or 'moderate' evidence of impact. In this case the Factor 2 score upgraded the Framework outcome category from yellow 'high threat' to orange 'not recovering' for seven plots and downgraded the outcome from green 'threat' to blue 'no threat' for two plots.

In view of the small number of plots for which Factor 2 scoring was possible, and the unequal sample size distribution across the outcome categories (only 2 plots in both the 'no threat and 'threat' categories vs 23 plots in the 'not recovering' category, Table 10) we were unable make any meaningful comparison between vegetation metrics and Framework outcome categories.

Table 10. Results of Factor 2 scoring and overall Framework outcomes for calcareous grassland. Framework outcomes are shown as: blue – 'no threat'; green – 'threat'; yellow – 'high threat'; orange – 'not recovering'; red – 'unfavourable no change'. See Table 1 for outcome category definitions.

	Factor 2 score							
Factor 1 score	Moderate evidence no impact	Weak evidence no impact	No evidence	Very weak	Weak	Moderate	Moderately strong	Strong
Very low								
Low	2					2		
Medium low								
Medium								
Medium High	1			4		7		
High				16				
Very High								

4. DISCUSSION

4.1 Trends in Scottish plant communities associated with N deposition

The results presented here represent probably the first comparative assessment of nitrogen deposition impacts across such a wide range of Scottish habitats. All 12 of the selected CSM habitats showed significant change in vegetation composition between the two surveys, and there were several general trends in vegetation metrics over time, which were seen across a number of habitats. Trends of decreasing Shannon H diversity, increasing graminoid cover, decreasing forb cover and increasing graminoid - forb cover index all match trends which have previously been reported to be associated with N deposition (Dise et al., 2011). The results of the analysis of change in vegetation metrics versus potential pollution, climatic and grazing drivers suggest however, that these general trends may have varying causes.

Nitrogen deposition was a significant driver of vegetation change in all 12 selected habitats, although the number and strength of the relationships varied. Relationships between vegetation change and N deposition were weakest for the lowland grassland habitats (lowland acid grassland and lowland meadow) and acidic oak woodland. In the case of the grassland habitats, which are likely to be actively managed, it might be expected that factors such as grazing would have a greater influence on vegetation composition than N deposition, and for lowland meadows the critical load is set correspondingly high at 20-30 kg N ha^{-1} y^{-1} (Bobbink & Hettelingh 2011). However, for woodlands, which generally experience higher rates of N deposition than other surrounding vegetation types, due to their greater surface area for interception of pollutants (NEGTAP 2001), the lack of relationships between vegetation change and N deposition is surprising. The critical load for acidic oak woodland is 10-15 kg N ha^{-1} y^{-1}, a range which was frequently exceeded in our sample dataset (Table 2). The apparent lack of significant responses to N deposition in this habitat may reflect the fact that our datasets described the composition of the woodland ground flora, while it is the epiphytic flora of bryophytes and lichens which is generally seen as the most sensitive component of this habitat to N deposition (Mitchell et al., 2005; Bobbink et al., 2010), and which is used to set the critical load value (Bobbink & Hettelingh 2011).

Relationships between N deposition and vegetation change were most frequent for the alpine habitat types (alpine dwarf shrub heath, alpine summits and snowbed), subalpine dry heath and calcareous grassland. All five of these habitats had numerous significant relationships between N deposition and vegetation change metrics, with reductions in Shannon H and increases in graminoid cover in response to N being common to all habitats. Responses of the cover of other species groups and changes in species richness in relation to N deposition were habitat specific however. Alpine habitats have low critical loads (5-10 kg N ha^{-1} y^{-1} for bryophyte dominated summits and snowbeds, 5-15 kg N ha^{-1} y^{-1} for alpine dwarf-shrub heaths) while deposition of N in alpine areas is often greater than surrounding areas due to orographic enhancement and the seeder-feeder effect (Choularton et al., 1988). In our sample set for these habitat types, mean N deposition was generally close to or above the current critical load (Table 2). Thus it is in line with expectations that these habitats should show some of the greatest effects of N deposition. Similarly, dry dwarf shrub heath has a moderate critical load (10-20 kg N ha^{-1} y^{-1}), the lower bound of which coincides with the mean N deposition of the sample plots (Table 2). This habitat also showed clear effects of N deposition on a range of vegetation metrics. The CSM category 12 – Calcareous grasslands (upland) – is a rather heterogeneous category including both upland calcareous grassland and calcareous snowbed communities. In general, calcareous grassland is seen as being less vulnerable to the acidification impacts of N deposition due to the higher buffering capacity of calcareous soils, but eutrophication impacts still occur (Bobbink et al., 2010; Dise et al., 2011). Our results suggested that N deposition is having a substantial effect on all vegetation metrics in this habitat except Ellenberg N, and on 3 out of 4 species richness metrics.

Along with identifying those habitats showing greatest N related change, the results of the regression analyses also point to which vegetation metrics, among those assessed, may be the best indicators for N deposition impacts (Table 11 and Annex 1). Relationships between N deposition and vegetation change metrics varied by habitat, and it is clear that no single set of metrics would be suitable to detect N deposition impacts across all habitats. In addition, since we pre-selected a set of metrics likely to respond to N deposition based on previous studies, a more comprehensive analysis for each habitat may reveal additional useful metrics. When developing an improved set of N deposition indicator metrics to include within SCM, we would recommend that this is done on a habitat by habitat basis. However, there were some metrics, such as Shannon H which were consistently associated with N deposition across many habitats. In general, it was the metrics based on vegetation composition data rather than species richness metrics which appeared to be most frequently associated with N deposition (Table 11). Calculating these metrics as part of the SCM process would, in some cases, require collection of more detailed species composition data than is currently recorded.

Table 11. Vegetation change metrics uniquely associated with (i.e. with no confounding factors) N deposition variables (change in 10 year N deposition or cumulative deposition between surveys) for each of the 12 selected JNCC CSM habitats. g/(g+f) – graminoid - forb cover index, v/(v+b) – vascular - bryophyte cover index. These relationships are shown graphically in Annex 1.

JNCC CSM Habitat type	Vegetation metrics
10. Lowland dry acid grasslands	None
12. Lowland meadows and upland hay meadows	graminoid cover, total richness
17. Lowland fens	g/(g+f), v/(v+b)
19. Acid grassland (upland)	Shannon H, graminoid cover
21. Alpine dwarf-shrub heath	Cover graminoids, cover forbs, total richness
23. Alpine summit communities of moss, sedge and three-leaved rush	Cover bryophytes, bryophyte richness
24. Blanket bog and valley bog (upland)	cover bryophytes
26. Calcareous grassland (upland)	Shannon H, cover bryophytes, total richness
35. Snowbed	Shannon H, total richness, bryophyte richness
41. Subalpine dry dwarf-shrub heath	Shannon H, v/(v+b)
45. Wet heath (upland)	Shannon H, total richness
47d. Acidic oak woodland	Ellenberg N, bryophyte richness

4.2 Performance of the framework

4.2.1 Factor 1

Factor 1 scores predicted significant N impacts in a wide range of habitats and the large proportion of high Factor 1 scores in alpine habitats, upland grasslands and blanket bog fitted our expectations and observations of which habitats would be most impacted by N. Factor 1 scores also predicted that woodland communities would be strongly impacted but this was not observed in our data. It is possible in this habitat that the Factor 1 scores could be a better indication of N impact than the vegetation change data, as the latter relates to ground flora species and may not reflect changes in the more sensitive epiphyte floras on which critical loads are based.

When comparing Factor 1 scores against the most N-related vegetation metrics however, in many cases there were no clear links between Factor 1 scores and the vegetation metric. This was either because the different Factor 1 score categories showed significant overlap in vegetation change metrics or because there was no logical trend in vegetation change metrics between categories. Significant differences in vegetation change metrics between Factor 1 categories occurred in only three out of twelve habitat categories.

Comparing Factor 1 scores against spatial patterns of vegetation metrics at the time of the second survey did not improve the performance of Factor 1. In a small number of habitats where there were significant differences in vegetation metrics between Factor 1 categories, there was some indication that changes tended to occur between Factor 1 scores of ‘very low’ and ‘low’, rather than between low and high scores. This may indicate that critical loads may be set too high in these habitats and changes are occurring before the critical load is reached. The issue of critical loads being potentially set too high for some habitats including calcareous grassland, lowland grasslands and upland heaths was previously highlighted in the JNCC Framework report (Jones et al., 2016b). More accurate underpinning data on critical loads for CSM habitats would be needed to improve Factor 1 performance.

The sensitivity analysis of Factor 1 scores versus N deposition values may also give some insight into why Factor 1 scores were not well related to observed vegetation change. Since uncertainties around the critical loads values and modelled deposition values are expressed as percentages (e.g. +/- 50%) this leads to deposition ranges associated with low Factor 1 scores being much narrower than those associated with high Factor 1 scores. It also leads to variation between habitats with low and high critical loads, since an upper critical load bound of e.g. 30 kg N ha^{-1} y^{-1} would be inflated much more than an upper limit of 10 kg N ha^{-1} y^{-1}. The uneven size of the N deposition ranges represented by the Factor 1 categories may reduce the likelihood of finding significant relationships between Factor 1 and vegetation metrics, especially when the amount of scatter in the N deposition vs. vegetation metric relationships is taken into account.

In general, while the results of our regression analyses suggested significant impacts of N deposition on vegetation change across most habitats, and Factor 1 scores predicted significant impacts of N on those habitats experiencing the greatest levels of exceedance, the Framework seemed to have a limited ability to predict N impacts on a site by site basis. While the Factor 1 scores across a large number plots as presented here gives some indication of the relative sensitivity of different habitat types, it seems unlikely that a Factor 1 score for a single site could give a reliable likelihood of N deposition impact.

4.2.2 Factor 2

In the single habitat tested (calcareous grasslands), the Factor 2 scores both upgraded and downgraded the outcome of the Framework scoring process for a minority of plots. These assessments were based on a single indicator, with strong confounding factors. Given the lack of strong indicators of N deposition for most habitats in SCM (less than one third of CSM habitats have a strong N indicator) it is unlikely that information recorded directly at the site level during SCM would have much influence on Framework outcomes for most habitats, leaving Framework outcomes very reliant on modelled N deposition values and the critical loads information. This highlights the importance of both ensuring that critical loads are as accurate as possible (to improve Factor 1 scoring) and including new vegetation metrics within SCM protocols that are able to indicate N deposition impacts at the site level. Jones et al. (2016c) in the original Framework report highlighted the issue of the lack of strong N indicators included within CSM monitoring protocols and also assessed the potential for modification of existing CSM targets to better reflect N deposition impacts. They concluded that while modification of existing targets may be possible for some lowland habitats, many upland habitats and lowland wetlands (which are particularly important in the Scottish context) would require the development of new targets.

4.3 Practical issues associated with applying the framework

Factor 1 and 2 scoring for the selected habitats was undertaken by SNH staff, using the JNCC supplied scoring spreadsheets in conjunction with data from the SNH SCM database to give site based information. A number of practical issues were encountered with the scoring process. For Factor 1 scoring, the main issue was with a lack of automation. The Factor 1 Calculation Spreadsheet includes text on the ‘Read Me’ tab suggesting that it can be used in an automated fashion for a number of sites/features at any one time:

“The spreadsheet can be used to look up a Factor 1 score (Exceedance Score) on an individual site/feature basis **or it can applied in a more automated manner to multiple sites/features**. The guidance presented below illustrates how to derive the score for a feature(s) at a single site.”

However, despite attempts, SNH found it impossible to develop an automated approach in using the spreadsheet and Factor 1 scoring had to be undertaken as a stepwise process for each plot individually. A second issue around the Factor 1 scoring is that the Framework is run using JNCC CSM habitat types, which are not the same as those used in the Scottish SCM process. Generating the correct Factor 1 score thus requires an accurate table of correspondences between these two habitat classifications. The mapping of the SNH standard feature types (used in SCM) onto the JNCC CSM habitat types is unclear for some habitat types, requiring further QA by Habitat Advisers. In some cases, there is more than one match for a feature type, or no clear match. This is particularly common for wetland habitat types.

When generating Factor 2 scores from the Framework, some of the issues encountered were similar to those for Factor 1 scoring. As with Factor 1 scoring, no automation was possible and generating the scores required manual working on a plot-by-plot basis. Generating scores also required accurate matching between the SNH SCM habitat classification and standard feature types and the JNCC CSM habitat classification. In addition to these issues, a major problem with generating Factor 2 scores is the lack of N indicators recorded during CSM. Only 12 out of 47 CSM habitats have strong N indicators and these are always confounded. More habitats have weak indicators of N deposition, but failure of a target may or may not be due to N deposition; the evidence is uncertain for the majority of habitat types. For this reason weak indicators do not influence the Factor 2 scoring process. Despite this, Factor 2 scoring sheets are made available for some habitats which do not have any strong N indicators, which can be somewhat misleading as to the number of habitats for which Factor 2 scoring appears to be possible. It was clear from the available data, the lack of strong N indicators and the requirements for matching between habitat correspondences that it would be difficult to use the additional Factor 2 scoring for many features should the Framework be adopted and rolled out more widely for Scottish assessments.

4.4 Recommendations on use of the framework

Based on the analyses contained in this report we would recommend that the Framework in its current form is used only as a supporting tool to give an indication of possible N deposition impacts on sites and features monitored through the SCM process. While the logical approach of the Framework is sound, and it provides a consistent and transparent means of using national scale deposition mapping data to assess risk to sites and features, including appropriate consideration of uncertainty, the paucity of the underlying data limits its ability to accurately predict N deposition impacts. The lack of appropriate N indicators recorded under the current CSM protocols also places a heavy reliance on the Factor 1 scores. While the impression of relative habitat sensitivity to N given by the distribution of Factor 1 scores did more or less correspond with current understanding of which habitats are likely to be most impacted by N, the limited correspondence between Factor 1 scores and measures of vegetation change within habitats suggests that the Framework has limited ability to discriminate which sites are at greatest risk of N related change. This may reflect problems with the underlying critical loads information and unfortunately this lack of N indicators and underlying critical loads data is especially acute for the upland habitats which are particularly prevalent in Scotland.

4.5 Future research to improve detection of N impacts through SCM

Detection and attribution of N deposition impacts on Scottish habitats could be improved by research in three key areas:

1. Improving underpinning knowledge of thresholds for N impacts on Scottish habitats.
2. Increased accuracy of N deposition measurement using on site bio-indicators.
3. Development of habitat specific, strong N indicators for incorporation into SCM protocols.

The Nitrogen Deposition Decision Framework protocol is a robust and transparent process for attributing N deposition impacts in a standard way across a large number of sites and habitats. Improving the data behind the framework to make it fit for purpose, should enable it to accurately indicate risk of N impacts, as originally intended.

4.5.1 Improving underpinning knowledge of thresholds for N impacts

Our lack of basic knowledge about the thresholds for N impacts on Scottish habitats, i.e. their critical loads, is likely to be a key issue around the current inability of the Framework to accurately predict N deposition impacts. Critical loads information is generally derived from two kinds of studies; experimental manipulation studies where N is added to plots and ecosystem responses are recorded, or survey based studies where vegetation composition data is collected over a range of sites and analysed in relation to modelled or measured N deposition rates. Both types of studies have strengths and weaknesses. In experimental studies the effect of manipulating N alone can be easily studied, but a critical load for impacts can be obscured by the limited resolution of the N addition levels applied. In addition, experimental studies may fail to detect impacts of N if the area they are located in has already been subject to long term background N deposition resulting in loss of sensitive species before the experiment begins. In the case of survey based studies, the ability to detect a critical load is improved by the greater resolution of N deposition levels (assuming a sufficient number of sites and length of deposition gradient) but the effects of N may be obscured by effects of variability in, for example, climate and vegetation management between different sites.

The current critical loads have been set using a variety of evidence from studies across Europe (Bobbink & Hettelingh 2011), with evidence from studies in the UK being a major contributor to the evidence base. However, there are many habitats for which critical loads are based on limited evidence and thus have a high degree of uncertainty surrounding them. Over time, as more information on the responses of habitats to N is gained, the critical loads are updated to reflect this. As noted in Annexe 1 of the JNCC Nitrogen Deposition Decision Framework report (Jones et al., 2016b) this generally involves the downward revision of critical loads as impacts become apparent at lower deposition levels. This has particularly been the case as increasing data becomes available on bryophyte and lichen responses, as these appear to be the most sensitive components of the vegetation in relation to N deposition in many habitats.

A call for more data analysis to underpin the critical loads values used in the Framework was one of the major recommendations in Annexe 1 of the JNCC Nitrogen Deposition Decision Framework report (Jones et al., 2016b). The authors noted that evidence from the UK since the last update to the N critical loads in 2010 (Bobbink & Hettelingh 2011) suggested that grasslands and heathlands in general and the CSM habitats lowland acid grassland, calcareous grassland and wet heath in particular, may have critical loads which are too high. They also noted that one third of CSM habitats had no primary data on which to judge N sensitivity and there was an urgent need for more data, with uplands and woodlands included among the priorities.

Survey studies provide probably the most cost effective means of gaining new evidence on the thresholds for N impacts on Scottish habitats. Existing survey data (Table 12) could be used for detailed habitat-level studies of responses to N deposition in the UK context, without the costs associated with new field data collection. The analyses presented in this report (which cover a limited number of metrics for a wide range of habitats) demonstrate that the impact of N deposition on vegetation composition can be detected using these data. More detailed analyses would allow thresholds for N impacts to be detected and the best indicator metrics for N deposition to be ascertained for each habitat (see Table 11). When sourcing datasets for this approach, those most suited to these analyses would be those where detailed information on lichen and bryophyte communities is included, since these are often the most sensitive components of the plant community. In many datasets, bryophytes and lichens are recorded only in a very superficial way and these data may be less suited to accurately determining a critical load.

Analyses of N impacts may be based either on datasets with repeat survey data, in which case change through time in response to changing N loads can be assessed, or on datasets from a single survey date in which case spatial gradients in N deposition can be used to infer N impacts. Data from one-off surveys spread over a long period of time may still be used for this type of analysis by assessing vegetation composition against metrics of N deposition and environmental variables at the time of survey. To date, the majority of analyses of vegetation change in relation to N deposition have focussed on acid grasslands and heathlands. However, data do exist to extend these analyses to a much wider range of habitats for which knowledge of N impacts is currently poor. Examples of habitats for which this approach could be used with the data resources assembled for the current project would include upland calcareous grassland, lowland fens, alpine summit communities, blanket bog, wet heath, dry heath and upland acid grasslands. By using additional data sources including one-off survey data, sample sizes could be considerably increased and a broader range of habitats included.

Resources for new survey data collection should be focussed on habitats for which survey data is currently lacking or not sufficiently well geographically distributed in relation to N gradients; this could include some less well represented alpine habitat types e.g. cliff and scree, fell fields, alpine flushes and wetlands, and woodlands with the exception of acidic oak woodland. It should also be noted that there may be benefits to cross-agency working where possible in regards to improving knowledge of N deposition impacts on habitats, since impacts and thresholds may be easier to interpret when a longer, whole UK N deposition gradient is used. The required information could be generated more efficiently by undertaking habitat analyses across their whole UK range and where new survey data are required, consideration should be given to UK-wide studies.

Improved knowledge of N deposition impacts and thresholds is an essential step in improving the detection and attribution of N deposition impacts on the natural heritage. Understanding which components of the ecosystem change in response to N deposition and the thresholds of their response is an essential pre-requisite both to predicting impacts based on modelled deposition rates (e.g. Factor 1 scoring) and to developing new metrics for N deposition impact which could be included in SCM (Factor 2).

Table 12. Details of example vegetation survey datasets with potential use in assessment of N deposition impacts on Scottish habitats. N.B. This is not an exhaustive list.

Dataset	Data holder	Habitat type(s)	Approx no. plots	Date range
Birse and Robertson	The James Hutton Institute	Alpine Grassland Moorland Wetlands Woodlands Maritime	6566 (survey 1) 1617 (survey 2)	1955-1990 and 2004-2014
Scottish Coastal Survey	The James Hutton Institute	Cliff Dune Grassland Heath Saltmarsh Wetland Woodland	3795 (survey 1) 2532 (survey 2)	1975-1977 and 2009-2013
McVean and Ratcliffe	Ross & Flagmeier, 2015	Alpine Grassland Moorland Wetland	254	1952-1959 and 2007-09
UK *Racomitrium* Heath Survey	The James Hutton Institute	Racomitrium heath	36 sites (8-16 plots each)	2006-7
Scottish snowbed monitoring network	SNH	Snowbeds	57 sites	1989-2016

4.5.2 Increasing accuracy of N deposition measurement

The second component included in the production of Factor 1 scores in the Framework is the N deposition rate at the site. Input to the Framework is generally in the form of modelled values of N deposition produced by the 5km resolution CBED model maintained by the Centre for Ecology and Hydrology. Within the Framework, the input deposition values are adjusted to take account of the considerable uncertainties associated with the modelling process (Jones et al., 2016b). The magnitude of uncertainty may vary by habitat type, being greatest in areas of complex topography, such as those associated with mountain terrain.

One method of reducing the uncertainties around the amount of N deposition at a site would be to use direct bio-monitoring of N exposure. Bryophytes in particular tend to accumulate N as they are reliant on atmospheric sources of nutrients. Bryophyte tissue N concentration has been demonstrated on several occasions to be a good match for modelled N deposition estimates (Baddeley et al., 1994; Pitcairn et al., 1995, 2001, 2003). Indeed, Rowe et al., (2017) propose a ‘moss enrichment index’ as a metric of N deposition. They demonstrate how an enrichment index could be developed using a range of bryophyte species to cover the low and high ends of the N deposition gradient. This kind of metric has the advantage that samples can be quickly and easily collected by non-specialists during SCM visits. The costs of N content analysis by an ISO accredited laboratory are in the order of £15 per sample, and a small number of samples per site (<10) would be sufficient to generate a reasonable estimate of N deposition.

Experience with previous surveys of N impacts in alpine ecosystems, however, suggests that when using *Racomitrium lanuginosum* as the indicator species, the fit between moss N content and modelled deposition values varies between habitats. In a study of *Racomitrium* heath Armitage et al., (2012, 2014) found a close correlation between modelled N deposition and moss N content. While in a study of alpine *Calluna* heath, Britton & Fisher (2007) found that altitude was a better predictor of N content than modelled N deposition. In the absence of direct measurements of N deposition (which are expensive and time consuming to perform) it is not possible to be certain whether it is the bio-indicator or the modelled deposition estimate which provides the more accurate data. While this approach could add useful information to improve Framework performance, since the uncertainties associated with deposition values are considerable (+/- 50%) it would be expensive to perform a proper validation of biomonitors for upland habitats, due to a lack of existing sites with N deposition measurements. We would suggest that resources would be better focussed in the first instance on improving underpinning knowledge of N impacts and thresholds and reducing critical loads uncertainties, as outlined above.

4.5.3 Development of N indicators for inclusion in SCM

Only twelve CSM habitat types currently have a strong N impact indicator metric and the development of new, habitat specific N indicators which can be applied in a consistent and repeatable way across sites and between years is a priority. The spirit of the CSM process is that it provides an appraisal of the conservation status of sites and features using site based evidence, and so strong N indicator metrics are a pre-requisite if changes in site condition are to be attributed to N deposition.

As our vegetation metric versus driver regression analyses in this report show, the best vegetation metrics for indicating N deposition impacts will vary by habitat (Table 11). Selection and development of the best N indicator metrics requires an underpinning knowledge of how each habitat responds to N deposition and its thresholds for response. As outlined above (section 4.5.1) development of accurate critical loads for N impacts and vegetation metrics to detect N impacts are closely interrelated and can be undertaken as part of the same analysis. Vegetation metrics recorded as part of SCM, which are essentially one off single values, require benchmarks against which they can be assessed to determine N impact. Such benchmark values can be derived from the studies of vegetation composition along N gradients used to determine critical loads, as is currently being explored by SEPA in their ‘Botanical Benchmarks’ project.

Inclusion of strong indicators of N deposition impacts in CSM protocols will likely require more detailed vegetation monitoring than is currently undertaken. At present the CSM monitoring targets in alpine habitats for example, are extremely simple, comprising only a handful of vegetation targets. While metrics such as total graminoid, forb or bryophyte cover (highlighted as potential N indicators in Table 11) could be simply implemented, others such as Shannon H index or total species richness would require detailed plot-level inventories of higher plants, lichens and bryophytes. Since these metrics will also vary spatially across a site, the power of CSM based monitoring to detect changes due to N deposition would be greatly enhanced by having permanent fixed monitoring plots.

Vegetation composition metrics are not the only potential indicators of N deposition impacts. N deposition affects many aspects of ecosystem structure and function in addition to the plant community. Rowe et al., (2017) set out a range of metrics, describing them as pressure metrics (measures of deposition rates), midpoint metrics (measures of changes in primarily chemical properties which may precede biodiversity change) and endpoint metrics (measures of biodiversity change). While both critical loads and CSM outcomes are generally based on biodiversity measures, which represent an endpoint of the changes induced by N deposition, it is possible to detect changes in ecosystem function due to N before biodiversity changes occur. When designing new N indicators to include in CSM, consideration needs to be given, therefore, as to whether monitoring of N impacts should be confined to impacts on biodiversity. It may be useful to include a directly measured chemical indicator such as the moss enrichment indicator (Table 13) in addition to biodiversity metrics. One point to note however is that while vegetation composition based N indicators could be readily identified from existing vegetation composition data, as part of the critical loads assessment process outlined in 4.5.1., calibration and testing of chemically based midpoint indicators would require new field data collection.

The range of potential metrics of N deposition impacts which could be considered for inclusion in CSM protocols is outlined in Table 13. We would recommend that a set of 2-4 N impact metrics is selected for each habitat based on habitat specific analyses of N deposition – metric relationships. Given the likely constraints on resources, our recommendation would be to focus initially on selection of vegetation composition based metrics for each habitat on the basis of analysis of existing survey data. This exercise could be combined with the development of more accurate critical loads to underpin Factor 1 scores, and would give the greatest enhancement of the Framework ability to attribute N deposition impacts for the least cost.

4.5.4 Summary of recommendations for future research

In summary, we recommend that future work to improve the detection of N deposition impacts on habitats through the SCM monitoring process should first focus on using existing survey data to improve both critical loads and selection of N relevant vegetation indicators though habitat based analyses of N impacts on vegetation. Priority should be given to those habitats where N impacts appear likely to be greatest and those where there is currently no relevant critical loads information. This would include upland calcareous grassland, dry and wet heaths and blanket bog and alpine habitats excluding dwarf shrub heaths. Second level priority should be given to those CSM habitats where there are currently no N indicators recorded in SCM (many upland habitats).

Once existing data have been used in this way to improve performance of the Framework we suggest looking at developing a direct metric for N deposition impact (e.g. Moss Enrichment Index as a measure of N saturation). This could then be included in the ensemble of N metrics recorded during SCM to provide an element of advance warning of potential N impacts before biodiversity changes occur.

Table 13. Potential metrics of N deposition impact for use in CSM.

Metric	Metric type	Strengths	Weaknesses	Additional data collection required?
Bryophyte tissue N content / Moss Enrichment Index (Rowe et al., 2017)	Pressure/ midpoint	• Potential as an indicator of both N deposition (pressure) and ecosystem N enrichment (midpoint) • Easy to collect samples in the field. • Not affected by differences between surveyors.	• Costs associated with chemical analysis. • Would require benchmarking values for a range of moss species to cover different habitat types.	Yes – for species specific benchmarking
Plant tissue N (higher plants)	midpoint	• May give an indication of ecosystem N saturation. • Easy to collect samples in the field. • Not affected by differences between surveyors.	• Costs associated with chemical analysis. • Varies seasonally and with age of the plant. • May be affected by the availability of other nutrients e.g. phosphorus. • Likely to vary spatially within a site. • Would require benchmarking and development to produce a robust indicator.	Yes
Soil N content or C:N ratio.	midpoint	• May give an indication of ecosystem N saturation. • Unlikely to vary seasonally.	• May take a long time for N response to become apparent. • High spatial variability so may need a large number of samples for accurate estimates.	Yes
Shannon diversity	endpoint	• Appears to be strongly related to N deposition over a range of habitats.	• Requires detailed species inventory during CSM • May be sensitive to variability between surveyors • May be influenced by other variables in some habitats.	Only for habitats without existing survey data.

Metric	Metric type	Strengths	Weaknesses	Additional data collection required?
Cover weighted mean Ellenberg N scores	endpoint	• Related to N deposition in some habitats.	• Not significantly related to N in all habitats and interpretation not always clear. • Requires detailed higher plant and bryophyte inventory (no N scores for lichens) • May be sensitive to variability between surveyors	Only for habitats without existing survey data
Cover of plant species groups (e.g. graminoids, forbs) and relative cover indices (e.g. g/(g+f), v/(v+b))	endpoint	• Appears strongly related to N deposition in some habitats (especially graminoid cover) • Doesn't require detailed species inventory.	• Variably influenced by other drivers. • May be sensitive to variability between surveyors	Only for habitats without existing survey data
Species richness metrics	endpoint	• Appear strongly related to N deposition in some habitats.	• Variably influenced by other drivers. • Requires detailed species inventory. • May be sensitive to variability between surveyors	Only for habitats without existing survey data
Nitrophile/nitrophobe index (Pitcairn et al., 2006)	endpoint	• Similar to Ellenberg N but may be more sensitive to N impacts.	• Not available for all habitats, best developed for woodlands. • Requires detailed species inventory. • Would require further development to cover wider range of habitats.	Only for habitats without existing survey data
APIS Lichen indicator species (Lewis 2012)	endpoint	• Useful as a metric of impacts in woodland habitats. • Gives an indication of declining/improving trend.	• Relates only to gaseous N pollution. • Does not reflect wet N deposition. • Only works for oak-birch woodland.	Yes

5. CONCLUSIONS

Long term vegetation change is apparent across the wide range of CSM habitat types investigated in this study. This vegetation change is attributable to the combined effects of N and S deposition, climate change and alterations in grazing management over the long term. There was clear evidence of a significant impact of N deposition in all habitat types studied, but the nature and magnitude of N impacts on vegetation composition varied on a habitat by habitat basis.

One of the main aims of this study was to test the ability of the Framework to predict N deposition impacts on protected areas. For our sample of 1409 plots comprising 12 CSM habitat categories, we found limited correspondence between Framework outcomes and recorded vegetation change. While Factor 1 scores derived for a large number of plots gave a general indication of the relative sensitivity of habitats to N impacts, we were not confident that assessments for a single site (as carried out during SCM) would produce usable results. Factor 2 scores had limited impacts on Framework outcomes due to the lack of N indicators included in current CSM protocols. While the Framework process provides a transparent means of attributing N impacts, taking account of current information and the relevant surrounding uncertainties, it is clear that deficiencies in the underlying knowledge of N deposition impacts for a large number of habitats, and thus the large uncertainties brought into the Framework process make the current Framework outputs of limited usefulness for alteration of SCM outcomes. We thus recommend that the Framework is used only as a supporting tool during SCM assessments.

Despite the issues with the Framework in its current form, there is scope to improve its performance to the point where it becomes a usable tool, by improving the underlying data on N impacts in Scottish habitats and reducing associated uncertainty. To date, detailed N impact assessments have been concentrated in a small number of habitats (acid grasslands, dry heathlands, alpine dwarf shrub heath, *Racomitrium* heath and Atlantic oak wood epiphyte communities). Existing vegetation composition datasets, however, provide a resource which could be used to produce assessments of N impacts, thresholds and N indicator metrics for a wide range of habitats. We recommend that utilisation of these data should be given the highest priority when choosing methods to improve performance of the Framework. Those habitats for which N-related vegetation change is predicted to be greatest and those habitats for which there are currently no N metrics in CSM should be the priority.

Direct measures of habitat N saturation status may provide an additional means of detecting N impacts on habitats before biodiversity changes become apparent. We recommend that consideration should be given to developing one or more of these metrics for inclusion in SCM protocols as part of an ensemble of N indicator metrics. While metrics such as the Moss Enrichment Index have been put forward in the scientific literature, they have not yet been tested across multiple habitats in the field and a programme of development and testing would be required to produce a usable metric for SCM.

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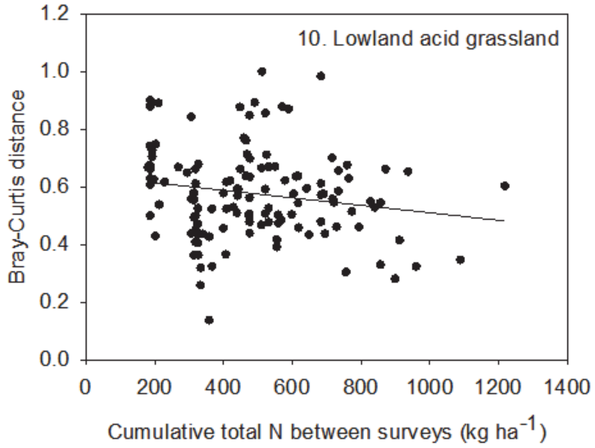
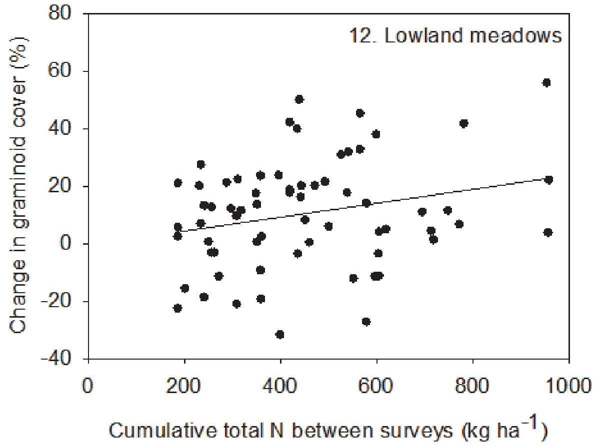
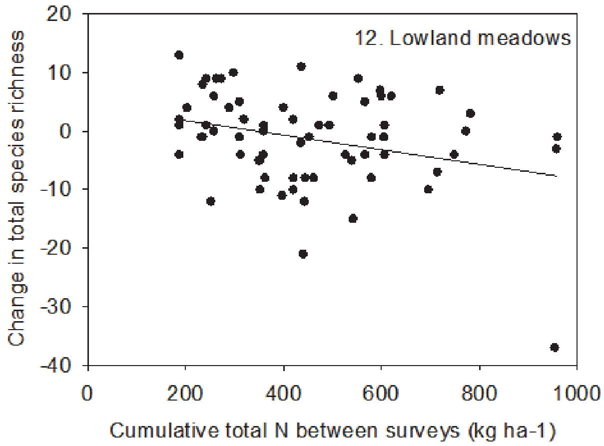
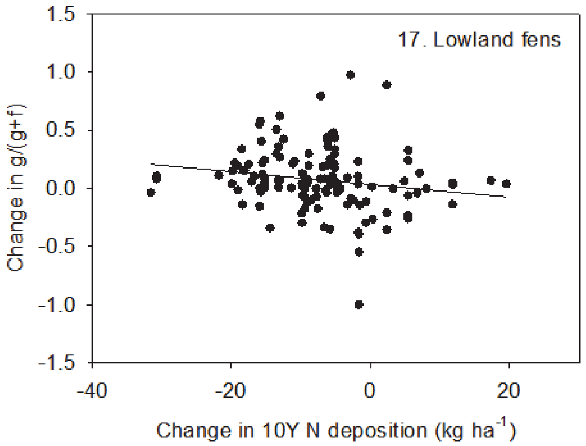
ANNEX 1: GRAPHS OF SIGNIFICANT RELATIONSHIPS BETWEEN NITROGEN DEPOSITION AND VEGETATION CHANGE METRICS NOT INFLUENCED BY OTHER DRIVERS FOR THE 12 SELECTED HABITATS

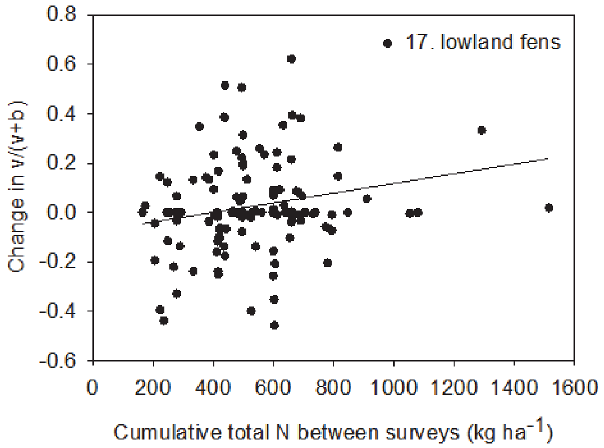
Annex 1: Graphical representations of the relationships between N deposition and vegetation change metrics which were not influenced by other drivers, for the 12 selected CSM habitats. Each point on the graph represents one plot, lines show significant linear regressions. Refer to Table 6 and 7 in the main report for details of regression results, significance and r^2 values.

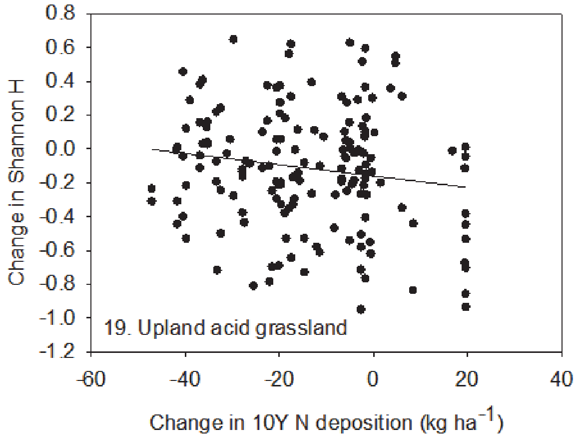

10. Lowland acid grassland
Bray-Curtis distance
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
1200
1400
Cumulative total N between surveys (kg ha-1)

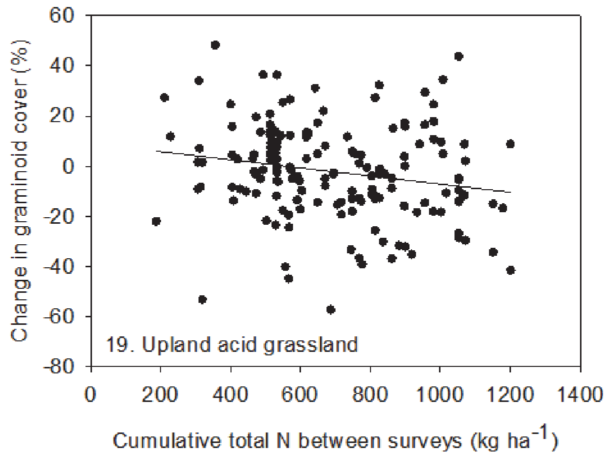

12. Lowland meadows
Change in graminoid cover (%)
80
60
40
20
0
-20
-40
0
200
400
600
800
1000
Cumulative total N between surveys (kg ha-1)

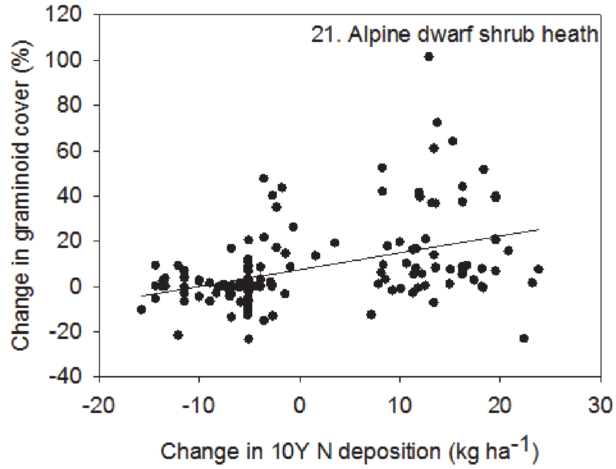

12. Lowland meadows
Change in total species richness
20
10
0
-10
-20
-30
-40
0
200
400
600
800
1000
Cumulative total N between surveys (kg ha-1)

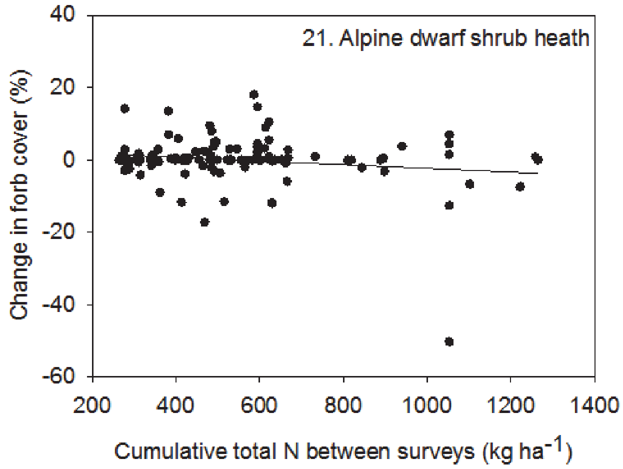

17. Lowland fens
Change in g/(g+f)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-40
-20
0
20
Change in 10Y N deposition (kg ha-1)

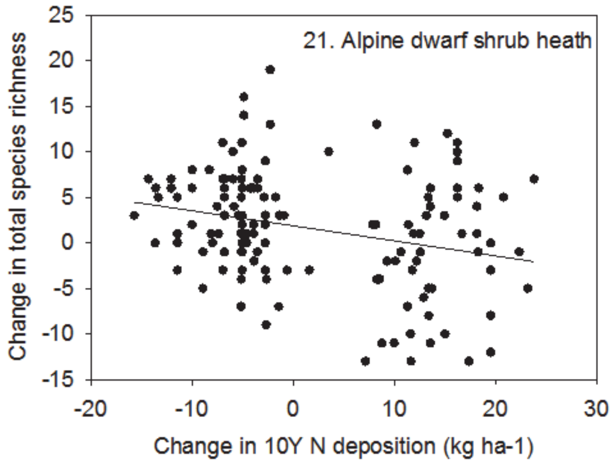

17. lowland fens
Change in v/(v+b)
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
200
400
600
800
1000
1200
1400
1600
Cumulative total N between surveys (kg ha-1)

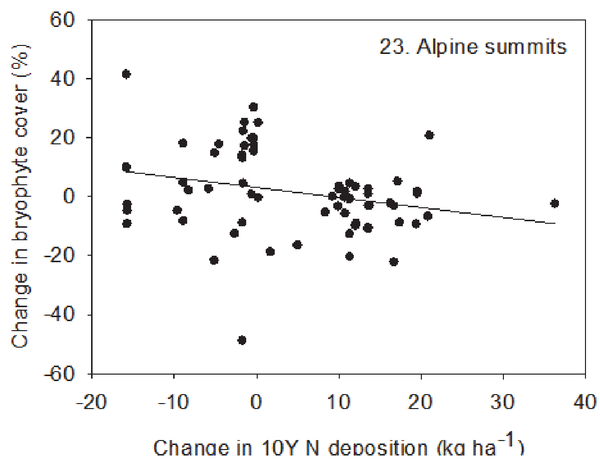

19. Upland acid grassland
Change in Shannon H
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-60
-40
-20
0
20
40
Change in 10Y N deposition (kg ha-1)

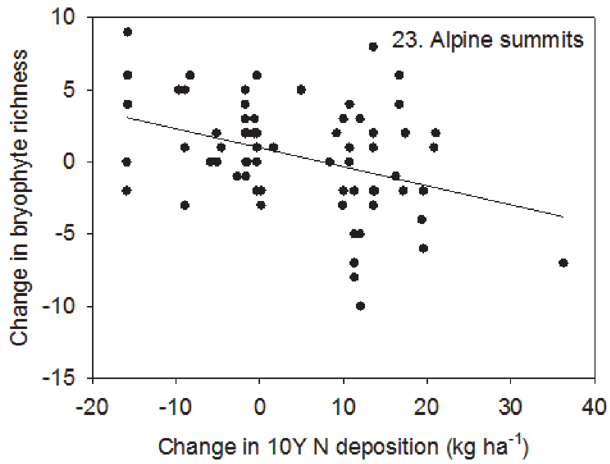

19. Upland acid grassland
Change in graminoid cover (%)
60
40
20
0
-20
-40
-60
-80
0
200
400
600
800
1000
1200
1400
Cumulative total N between surveys (kg ha-1)

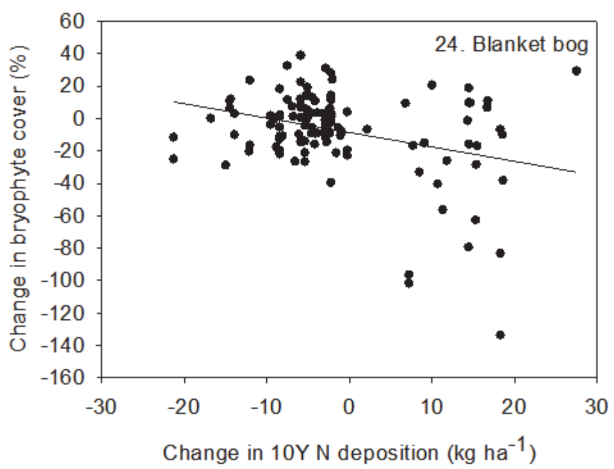

21. Alpine dwarf shrub heath
Change in graminoid cover (%)
Change in 10Y N deposition (kg ha^{-1})

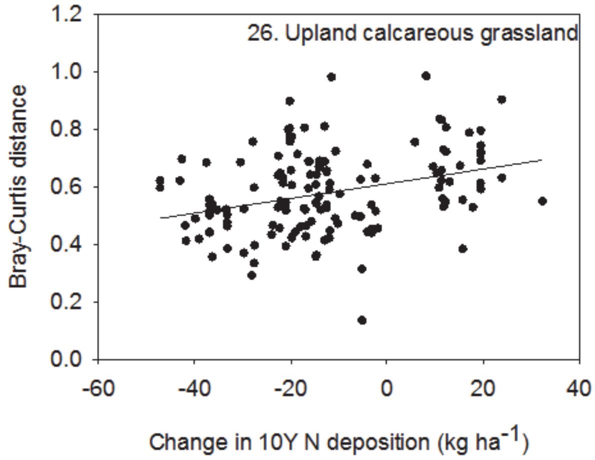

21. Alpine dwarf shrub heath
Change in forb cover (%)
Cumulative total N between surveys (kg ha^{-1})

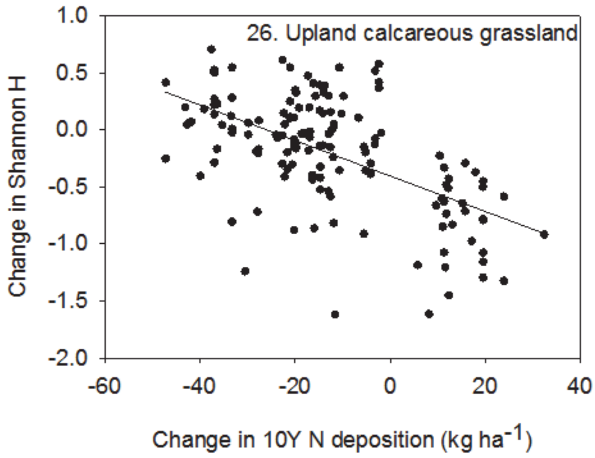

21. Alpine dwarf shrub heath
Change in total species richness
Change in 10Y N deposition (kg ha-1)

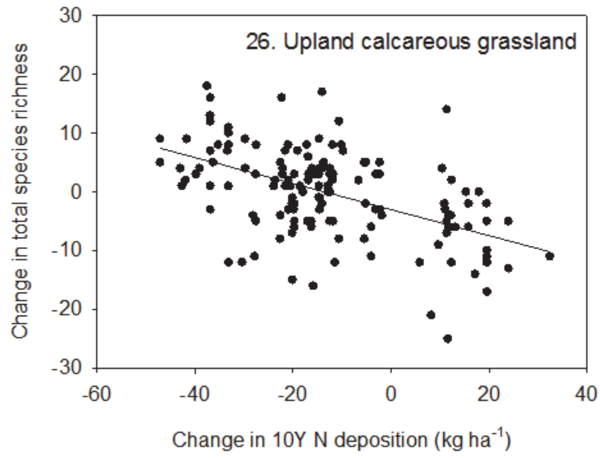

23. Alpine summits
Change in bryophyte cover (%)
Change in 10Y N deposition (kg ha^{-1})

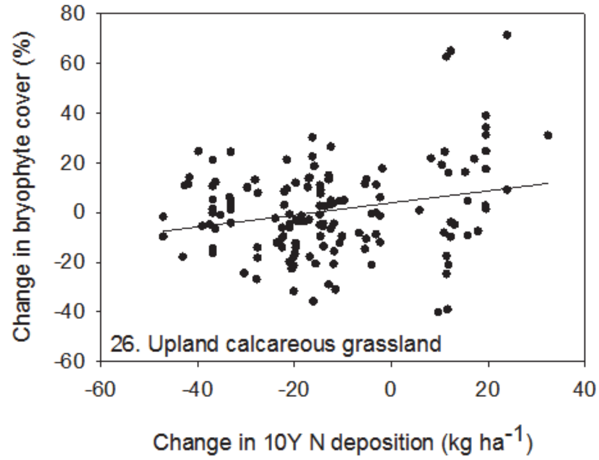

23. Alpine summits
Change in bryophyte richness
Change in 10Y N deposition (kg ha^{-1})

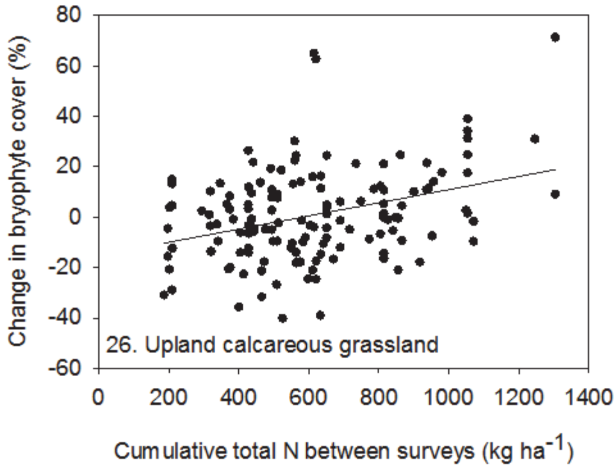

24. Blanket bog
Change in bryophyte cover (%)
Change in 10Y N deposition (kg ha^{-1})

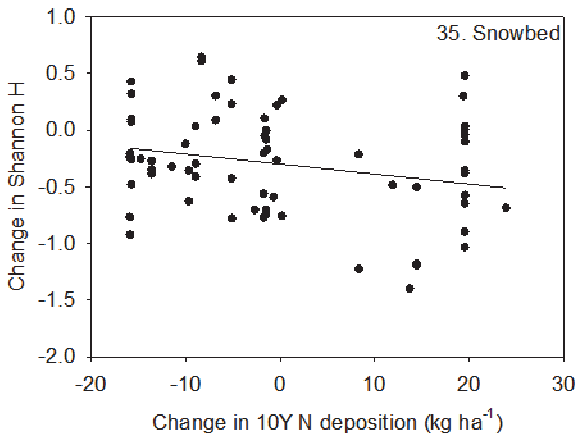

26. Upland calcareous grassland
Bray-Curtis distance
Change in 10Y N deposition (kg ha-1)

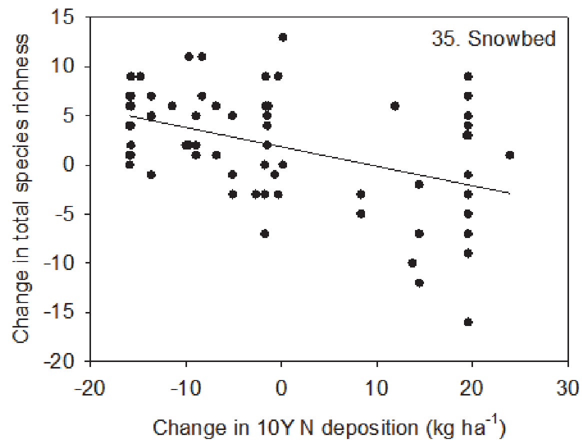

26. Upland calcareous grassland
Change in Shannon H
Change in 10Y N deposition (kg ha-1)

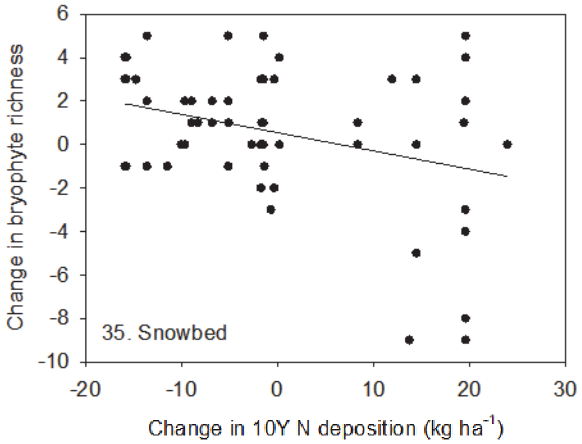

26. Upland calcareous grassland
Change in total species richness
Change in 10Y N deposition (kg ha-1)

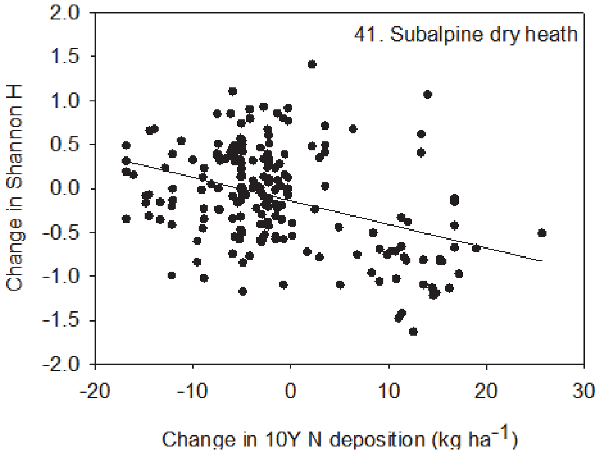

26. Upland calcareous grassland
Change in bryophyte cover (%)
Change in 10Y N deposition (kg ha-1)

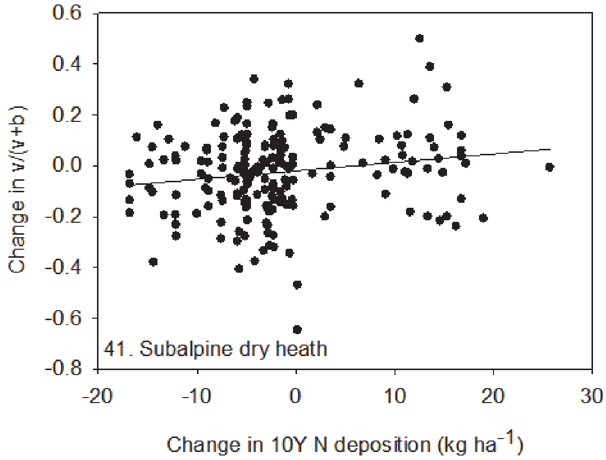

26. Upland calcareous grassland
Change in bryophyte cover (%)
Cumulative total N between surveys (kg ha-1)

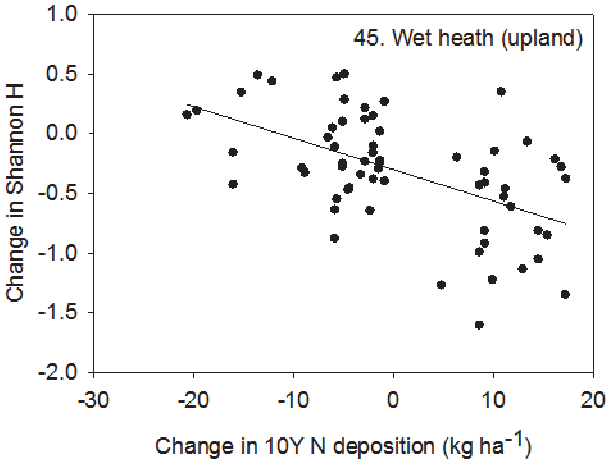

35. Snowbed
Change in Shannon H
Change in 10Y N deposition (kg ha-1)

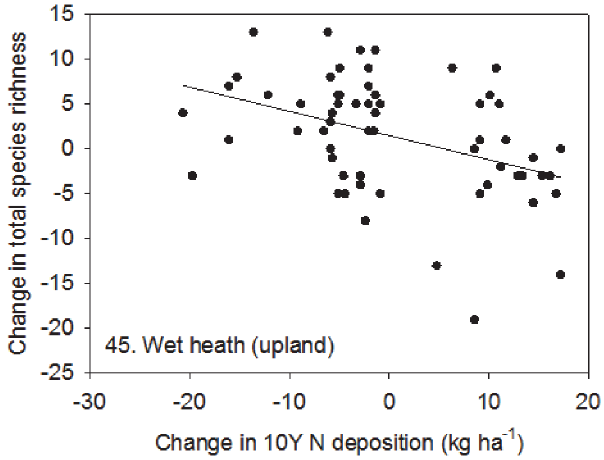

35. Snowbed
Change in total species richness
Change in 10Y N deposition (kg ha-1)

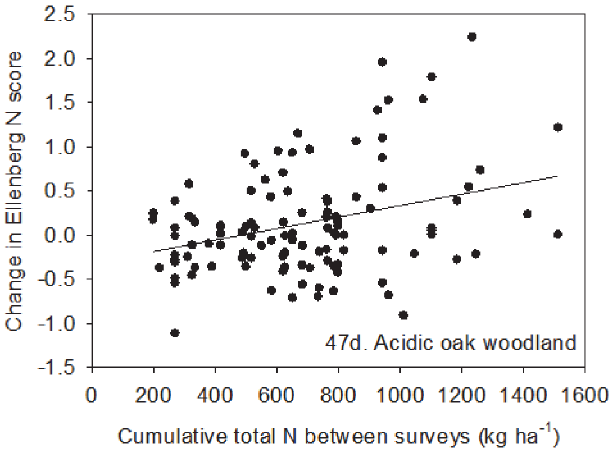

35. Snowbed
Change in bryophyte richness
Change in 10Y N deposition (kg ha^{-1})

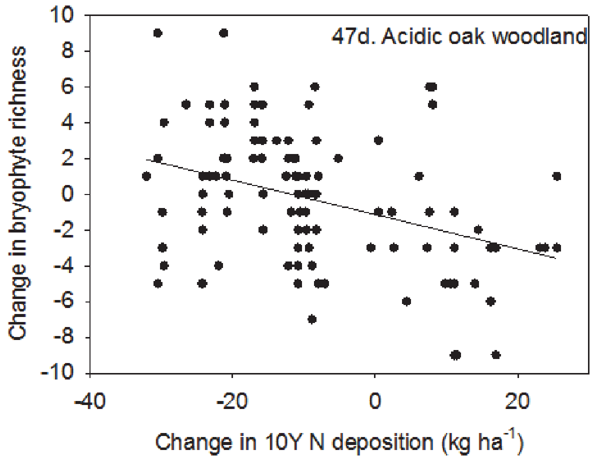

41. Subalpine dry heath
Change in Shannon H
Change in 10Y N deposition (kg ha^{-1})


41. Subalpine dry heath
Change in v/(v+b)
Change in 10Y N deposition (kg ha^{-1})


45. Wet heath (upland)
Change in Shannon H
Change in 10Y N deposition (kg ha^{-1})


45. Wet heath (upland)
Change in total species richness
Change in 10Y N deposition (kg ha^{-1})


47d. Acidic oak woodland
Change in Ellenberg N score
Cumulative total N between surveys (kg ha^{-1})


47d. Acidic oak woodland
Change in bryophyte richness
Change in 10Y N deposition (kg ha^{-1})

ANNEX 2: RESULTS OF THE COMPARISONS BETWEEN VEGETATION METRICS AND FACTOR 1 SCORES

Annex 2: Results of the comparisons between vegetation metrics and Factor 1 scores. Means ± S.E. are shown for each Factor 1 score category in each CSM habitat type. Blank rows indicate that there were no plots with that Factor 1 score for that habitat. Blank columns indicate that a metric was not uniquely associated with N deposition (see main report). BCD – Bray Curtis distance; EN – Ellenberg N score. With the exception of BCD, all values shown represent change in the metric value between surveys.

CSM habitat type	Factor 1 score	BCD	Total species richness	Shannon index	g/(g+f)	v/(v+b)	Graminoid cover	Forb cover	Bryophyte cover	Bryophyte richness	EN
		mean ± SE									
10. Lowland dry acid grasslands	NS										
	VL	0.68 ± 0.03									
	L	0.52 ± 0.02									
	ML	0.47 ± 0.12									
	M										
	MH	0.61 ± 0.02									
	H	0.48 ± 0.04									
	VH										
12. Lowland meadows and upland hay meadows	NS										
	VL		3.22 ± 1.44				1.82 ± 3.04				
	L		-3.79 ± 1.65				13.77 ± 4.69				
	ML		-2.56 ± 1.79				13.29 ± 3.75				
	M		-2.00 ± 1.00				13.02 ± 9.12				
	MH										
	H										
	VH										

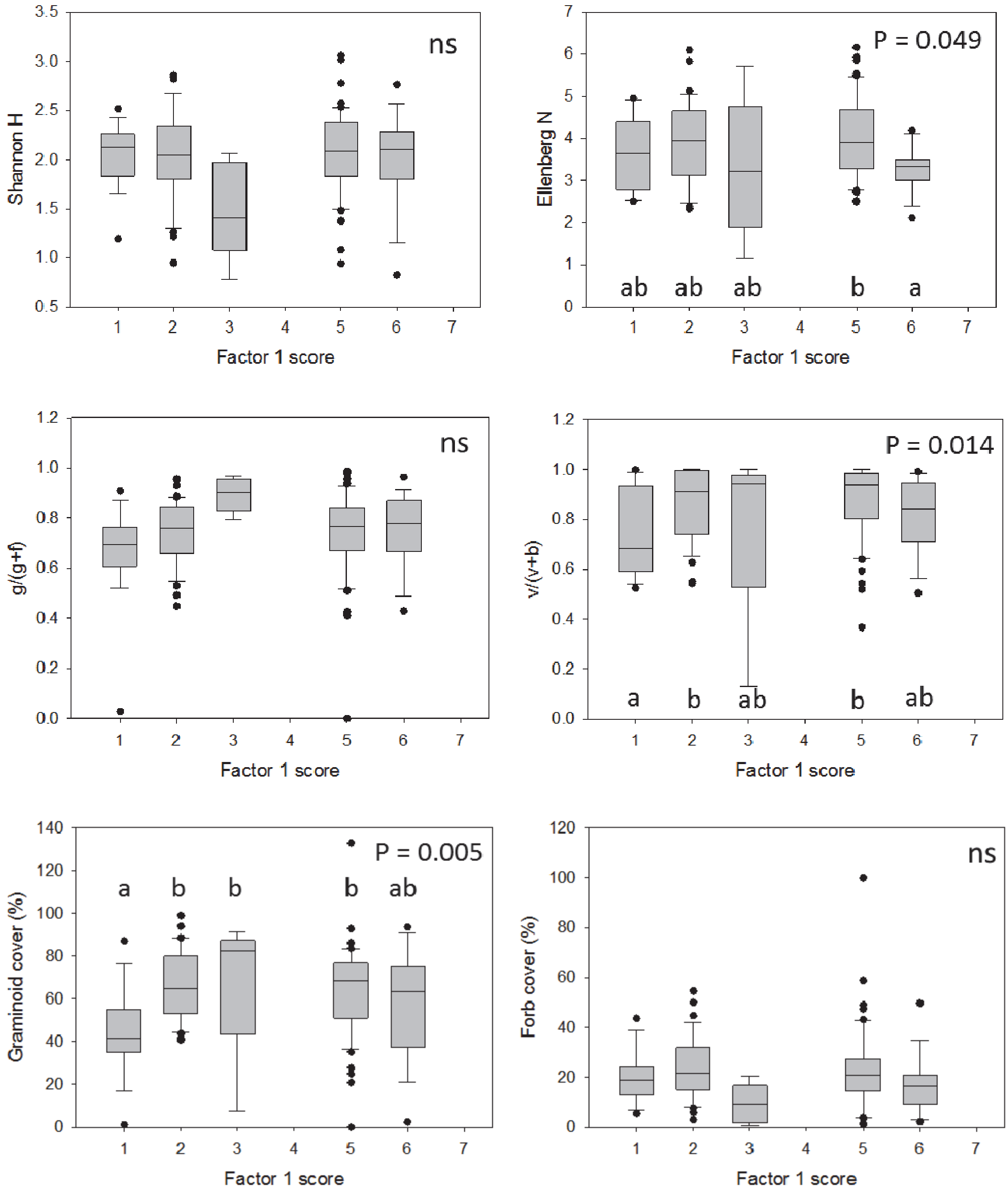
CSM habitat type	Factor 1 score	BCD	Total species richness	Shannon index	g/(g+f)	v/(v+b)	Graminoid cover	Forb cover	Bryophyte cover	Bryophyte richness	EN
		mean ± SE									
17. Lowland fens	NS				0.02 ± 0.05	-0.03 ± 0.03					
	VL				0.03 ± 0.06	-0.09 ± 0.08					
	L				0.14 ± 0.07	-0.02 ± 0.06					
	ML				0.29 ± 0.07	0.14 ± 0.06					
	M				0.09 ± 0.01	-0.04 ± 0.03					
	MH				0.11 ± 0.05	0.06 ± 0.04					
	H				0.04 ± 0.02	0.06 ± 0.05					
	VH										
19. Acid grassland (upland)	NS										
	VL			-0.42 ± 0.21			2.65 ± 14.06				
	L			-0.02 ± 0.10			-0.47 ± 7.54				
	ML			-0.25 ± 0.10			3.52 ± 5.00				
	M										
	MH			-0.1 ± 0.04			-4.45 ± 2.01				
	H			-0.1 ± 0.05			-1.51 ± 2.44				
	VH										
21. Alpine dwarf-shrub heath	NS										
	VL										
	L										
	ML		1.93 ± 0.76				8.48 ± 2.09	1.06 ± 0.59			
	M		-8.00 ± 2.00				54.61 ± 46.98	9.98 ± 8.02			
	MH		1.79 ± 0.87				7.87 ± 2.41	0.74 ± 0.67			
	H		1.33 ± 1.09				5.5 ± 3.04	-5.44 ± 2.73			
	VH										
23. Alpine summit communities of moss, sedge and three-leaved rush	NS										
	VL										
	L										
	ML										
	M										
	MH								-2.01 ± 2.34	-1.68 ± 0.88	
	H								3.53 ± 2.49	1.56 ± 0.52	
	VH								0.68 ± 5.58	-0.29 ± 1.41	

CSM habitat type	Factor 1 score	BCD	Total species richness	Shannon index	g/(g+f)	v/(v+b)	Graminoid cover	Forb cover	Bryophyte cover	Bryophyte richness	EN
		mean ± SE									
24. Blanket bog and valley bog (upland)	NS										
	VL										
	L										
	ML								-9.85 ± 10.74		
	M										
	MH								-5.71 ± 2.53		
	H								-7.94 ± 3.89		
	VH								-7.91 ± 6.58		
26. Calcareous grassland (upland)	NS										
	VL	0.63 ± 0.05	-0.91 ± 2.32	-0.35 ± 0.20					-6.90 ± 4.82		
	L	0.57 ± 0.02	1.54 ± 1.05	-0.04 ± 0.07					-2.07 ± 2.37		
	ML										
	M										
	MH	0.58 ± 0.02	-2.09 ± 0.94	-0.27 ± 0.06					-1.34 ± 2.58		
	H	0.57 ± 0.02	1.42 ± 1.58	-0.2 ± 0.09					9.54 ± 3.00		
	VH										
35. Snowbeds	NS										
	VL										
	L										
	ML		4.20 ± 2.75	-0.29 ± 0.31						1.20 ± 0.86	
	M										
	MH		-0.44 ± 2.20	-0.43 ± 0.17						0.56 ± 1.00	
	H		1.96 ± 0.78	-0.27 ± 0.06						0.47 ± 0.48	
	VH										
41. Subalpine dry dwarf-shrub heath	NS										
	VL			0.01 ± 0.14		0.00 ± 0.04					
	L			-0.16 ± 0.07		-0.01 ± 0.02					
	ML			-0.12 ± 0.09		0.01 ± 0.02					
	M										
	MH			-0.09 ± 0.06		-0.06 ± 0.02					
	H			0.13 ± 0.18		-0.11 ± 0.07					
	VH										

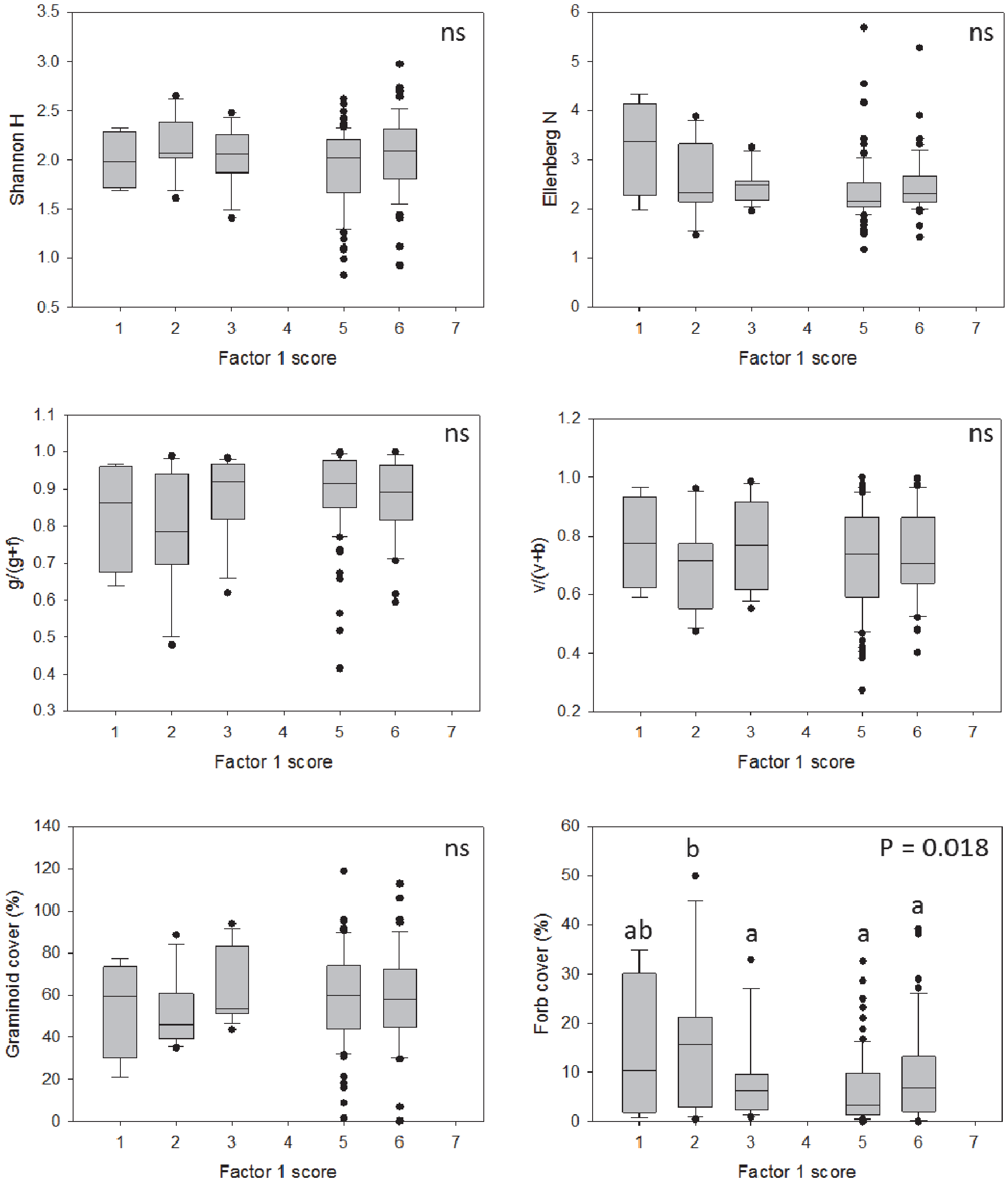
CSM habitat type	Factor 1 score	BCD	Total species richness	Shannon index	g/(g+f)	v/(v+b)	Graminoid cover	Forb cover	Bryophyte cover	Bryophyte richness	EN
		mean ± SE									
45. Wet heath (upland)	NS										
	VL		4.38 ± 2.85	-0.28 ± 0.21							
	L		0.21 ± 1.18	-0.43 ± 0.09							
	ML		3.67 ± 1.18	-0.05 ± 0.11							
	M										
	MH		-0.21 ± 1.86	-0.33 ± 0.13							
	H										
	VH										
47d. Acidic oak woodland	NS										
	VL										
	L									1.50 ± 1.50	0.08 ± 0.15
	ML									0.00 ± 0.64	-0.07 ± 0.07
	M										
	MH									-0.29 ± 0.58	0.18 ± 0.10
	H									-0.66 ± 0.64	0.24 ± 0.11
	VH										

ANNEX 3: RESULTS OF THE COMPARISONS BETWEEN FACTOR 1 SCORES AND VEGETATION METRICS AT SECOND SURVEY FOR SIX SELECTED HABITATS

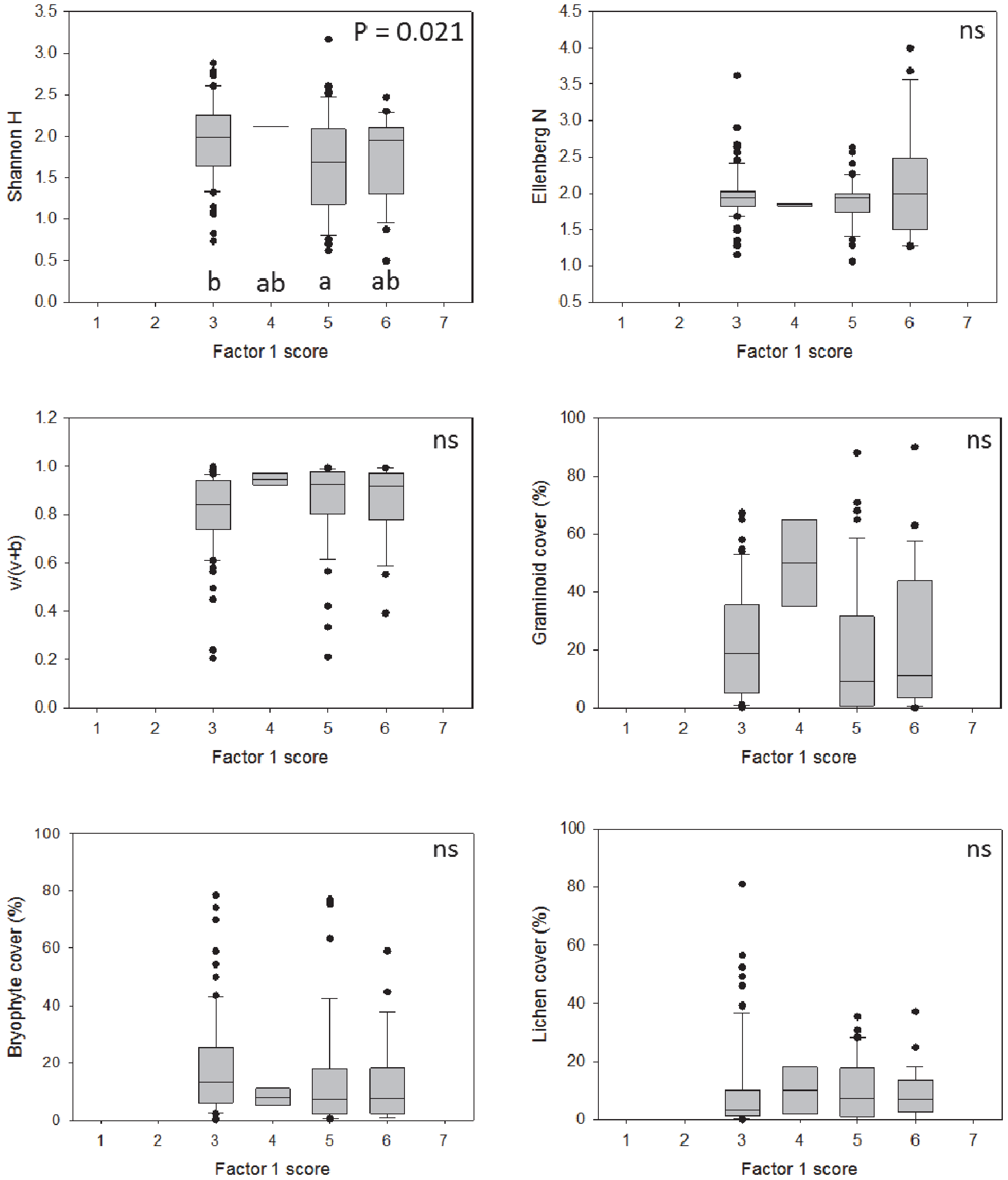
Annex 3. Box plots of relationships between Factor 1 score and vegetation metrics at re-survey for 6 selected CSM habitat types. Factor 1 scores are indicated numerically: 1 – 'very low', 2 – 'low', 3 – 'medium-low', 4 – 'medium', 5 – 'medium-high', 6 – 'high', 7 – 'very high'. For each Factor 1 category, horizontal lines show, from the bottom, the lower quartile, the median and upper quartile. The error bars below and above the boxes show the 10^{th} and 90^{th} centiles respectively. Dots are outlying values. The P value shown in each panel is the significance of an overall difference between Factor 1 categories (unequal sample size ANOVA in Genstat v18). Where there is a significant effect, Factor 1 score categories not sharing the same letter are significantly different at $P<0.05$.



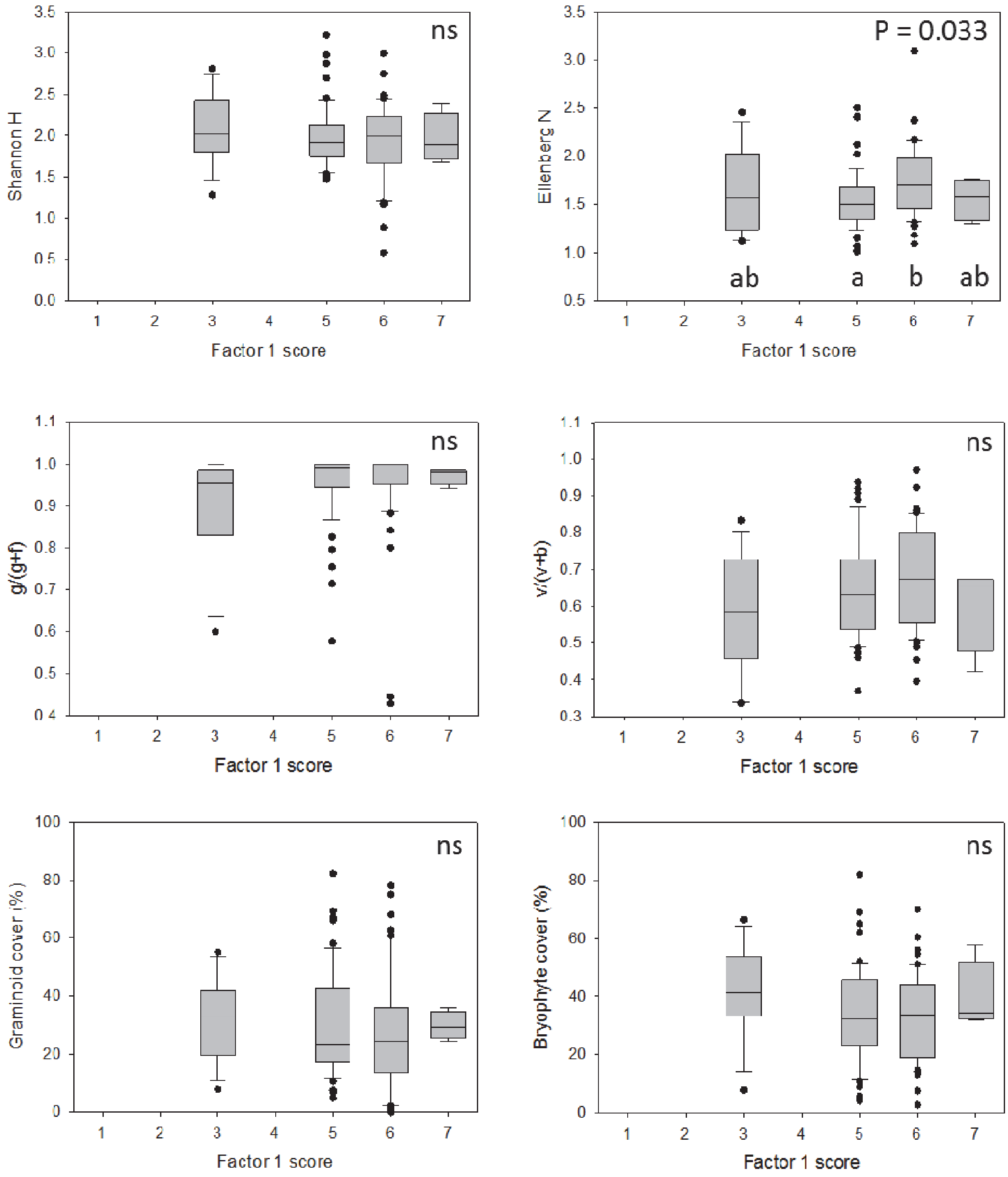
Annex 3a. Relationships between Factor 1 score and vegetation metrics at re-survey for CSM habitat 10. lowland acid grassland.



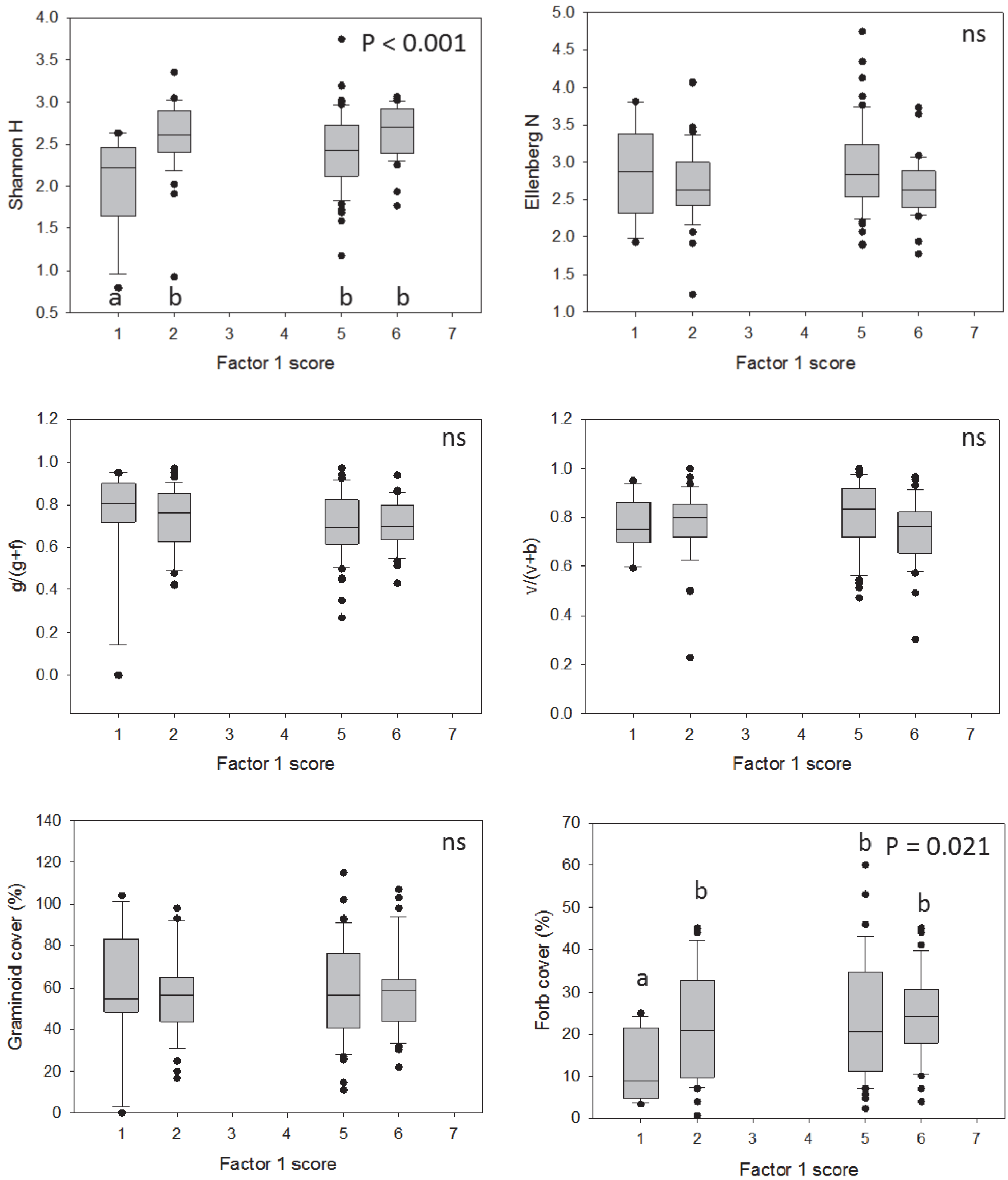
Annex 3b. *Relationships between Factor 1 score and vegetation metrics at re-survey for CSM habitat 19. Upland acid grassland.*



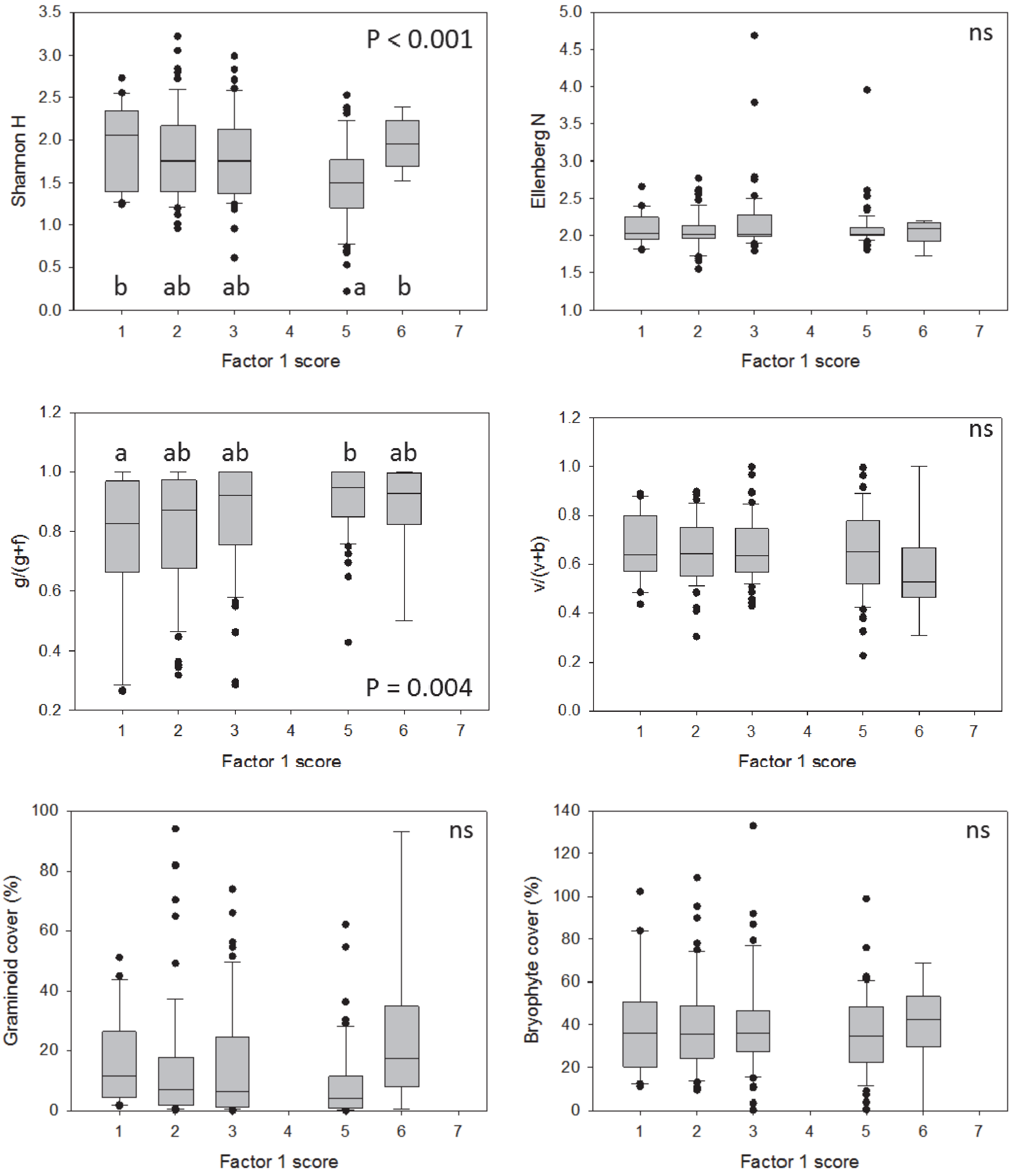
Annex 3c. *Relationships between Factor 1 score and vegetation metrics at re-survey for CSM habitat 21. Alpine dwarf-shrub heath.*



Annex 3d. *Relationships between Factor 1 score and vegetation metrics at re-survey for CSM habitat 24. Blanket bog.*



Annex 3e. *Relationships between Factor 1 score and vegetation metrics at re-survey for CSM habitat 26. Upland calcareous grassland.*



Annex 3f. *Relationships between Factor 1 score and vegetation metrics at re-survey for CSM habitat 41. Subalpine dry dwarf shrub heath.*

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