IDENTIFYING HABITATS AT RISK OF SPECIES LOSS DUE TO ENVIRONMENTAL CHANGE.

Deliverable 2.2d for the

Project D5-2 Climate Change Impacts on Natural Capital

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The James Hutton Institute

Summary

This report provides a first assessment of which Scottish habitats contain the highest proportion of species that might be at risk from environmental change. The approach combines quadrat-based information on community composition from a resurvey of Scottish habitats with a set of environmental preference data relating to climate, edaphic and disturbance preferences.

The combined data allows for the identification of species within each habitat that display preferences far from the mean preference of the species in the habitat, and to aggregate this to identify habitats with the highest proportion of species that might be at risk of environmental change due to the linkage between the preference values and known environmental gradients.

Key Messages:

The habitats with the most species at risk of increased temperatures or changing rainfall patterns are those mainly alpine (mountain top) habitats.

Grassland habitats, particularly fertile ones appeared most at compositional risk in terms of increased nitrogen pollution, whereas recovery from past levels of nitrogen deposition may see biggest changes in wetlands.

Analysis of disturbance indicators suggested moorlands were at most risk of species change if disturbance frequency declined, but at most risk if disturbance severity increased. Wetlands and grasslands were most at risk of both increased and decreased level of grazing.

Advances in Technical Capabilities

What this development facilitates is an ability to look at higher resolution as to which habitats might be affected by further climate change or from changes in other environmental drivers. We can use this methodology to identify habitats and habitat types with the highest proportions of species likely to be at risk from different changes in the environment, whether climate, pollution or disturbance.

This identification of habitats most at risk of changing composition could be used to direct resources for further monitoring and research or for mitigation management.

Contents

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Introduction

The purpose of this report is to describe an approach to assess Scottish habitats in terms of the risks they face from environmental change.

The context is to build an understanding of what projected climatic changes may mean for Natural Capital in Scotland. This report is a Deliverable for the Strategic Research Programme project 'Climate Change Impacts on Natural Capital' (JHI-D5-2).

The aim is to identify Scottish habitats that are most at risk in terms of their plant species composition from changes in climate, changes in pollution or changes in management.

This serves as an underpinning ability to provide risk and opportunity assessments of climate change impacts on Natural Capital assets at both a high spatial and temporal resolution. Please note: a follow-on Deliverable (D2.1b) assesses issues of changes in extremes.

The objective is to combine information on the plant composition of Scottish habitats and the environmental preferences of those species to assess which habitats contain the most species likely to be affected by environmental change. In turn this prioritisation could be used to direct resources for further research or for mitigation management.

Hence this report demonstrates the increasing capabilities within the D5-2 project (and others within the Strategic Research Programmes) to assess climate change impacts on Scotland's Natural Capital.

As a broader objective, subsequent research and Deliverables produced by the Climate Change Impacts on Natural Capital project will focus on improving the list of environmental preferences by integrating information on distribution with climate indices more relevant to plant growth than just temperature and rainfall in the context of the question 'what are the consequences on Natural Capital assets and their ability to both provide ecosystem services and serve as the basis for Nature Based Solutions?'.

Details and outputs from the project are available here:

Climate Change Impacts on Natural Capital | The James Hutton Institute

Advancing analytical capability

To facilitate further climate change impacts analysis on Natural Capital assets, technical developments in the project have advanced the analytical capability by:

- Linking information on species composition of Scottish habitats to three sets of information on environmental preferences of the individual species within those habitats.
- Developing a methodology to identify which species within a habitat might be at risk of environmental change: in effect species that differ markedly from the mean preferences present in the habitat.
- Using the methodology to identify habitats and habitat types with the highest proportions of species likely to be at risk from different changes in the environment, whether climate, pollution or disturbance.

The benefit of this technical development is that the identification of habitats most at risk of changing composition could be used to direct resources for further monitoring and research or for mitigation management. This would allow for more cost-effective use of the resources available for conservation and habitat management.

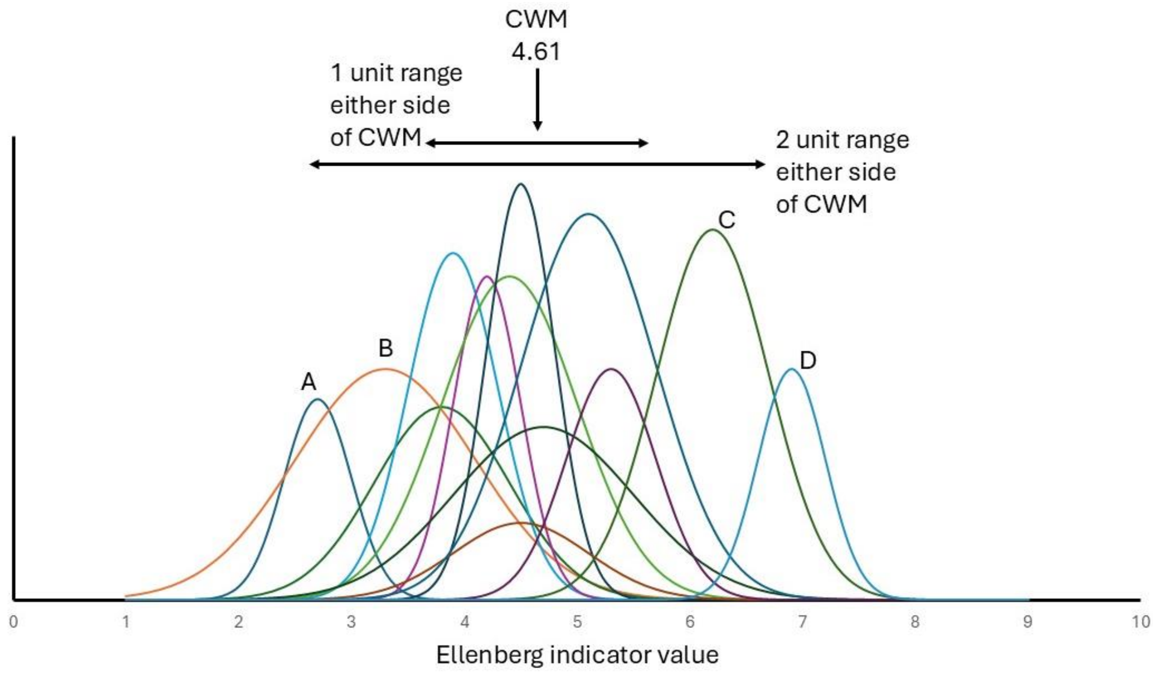
Background

Common approaches to assess how species may react to changing environmental conditions have usually used Species Distribution Models. These construct a habitat niche based on the current conditions experienced across sites where the species occurs using a variety of statistical approaches. The models are then used to identify areas where the species could occur under future climatic conditions and assessments are made as to changes in area and the likelihood of range shifts depending on dispersal mechanisms (e.g. Bateman et al. 2013, Franklin 2010). The resulting species models then have to be linked to habitats to assess which habitats may need mitigation management to prevent species losses.

This type of modelling approach is data hungry and has a number of methodological issues as input data on range tends to be two dimensional (latitude and longitude) whilst altitude is an important factor. Species may occur only at high altitudes in the warmer part of their range, and range expansion in cooler areas may include spreading upwards as well as polewards.

An alternative approach is to focus on the habitat level and to identify species at risk through identifying those species at the edge of functional space (the range of traits in multidimensional space occupied by a particular community) that are likely to be at risk of being lost from the community if environmental conditions change. Species are distributed along environmental gradients such that they occur at highest frequency/cover at their optimum conditions. Instead, if the species composition at a site can be displayed as the species distributions along an environmental gradient, then the relative positions of species in that environmental gradient can be visualised (Figure 1). The gradient can be replaced by an indicator value, so the species can be lined up relative to the community weighted mean (CWM, the weights being the species abundances). Species that differ widely from the CWM may be those most at risk if conditions change as their optimum is a long way from the current conditions.

Figure 1. Species relative abundances at a site displayed as their abundances along a gradient of environmental conditions. Species A has an indicator value more than two units lower than the CWM (community weighted mean) and could be at risk if conditions changed driving the system to one characterised by plant with higher indicator values. Species D has an indicator value more than two units higher than the CWM and would therefore be at risk is the community shifted to one characterised by lower indicator values. Species B and C differ from the mean by more than one unit. They would be at risk if conditions changed, but less so than species A and D.



Methodology

We have taken vegetation quadrat data from the resurvey of the Birse and Robertson dataset (Britton et al. 2009, 2017a, 2017b, Hester et al. 2019, Mitchell et al. 2017) and linked these to information on climate preferences (Hill et al. 2004, Hill et al. 2007, Pakeman et al. 2022), environmental preferences (Ellenberg 1988, Tichý et al. 2023) and associations with different levels of disturbance (Midolo et al. 2023, together referred to as traits below).

Climate preferences were calculated based on the average climate of the 10 km grid cells that species occurred in (Figure 2). The two species *Arctostaphylos alpinus* and *Cirsium acaule* have different distributions and hence quite different climate preferences. The mean January temperatures of these 10 km grid cells is 1.6°C for *A. alpinus* and 3.7°C for *Cirsium acaule*, with mean July temperatures of 11.6C° and 16.1°C and precipitation levels of 1750 mm and 742 mm, respectively.

Ellenberg indicator values were developed to classify species' habitat niches and the types of habitat conditions which contain their peak occurrences (Ellenberg 1988). They are correlated to a range of plant functional traits, for example, the Ellenberg nitrogen indicator is correlated to leaf traits such as specific leaf area (Bartelheimer & Poschlod 2016). A harmonised data set has recently been produced for Europe (Tichý et al. 2023).

The existence of indicator values that describe climate and edaphic niches has driven the production of indicator values that describe the niches of species along disturbance gradients (Midolo et al. 2023). Five types of indicator have been developed that link species optima to disturbance severity, disturbance frequency, the frequency of mowing, the amount of biomass removed by grazing and the amount of biomass destroyed by soil disturbance.

For each trait we have calculated a community weighted mean (CWM) based on the cover of the species present – a more dominant species contributes more to the mean than a species that is present as a small proportion of the cover. For the analysis below we have identified the mean proportion of species present that differ from the weighted mean at various thresholds to identify those habitats where more species might be at risk of loss if conditions change.

Figure 2. Distribution maps of *Arctostaphylos alpinus* and *Cirsium acaule*.

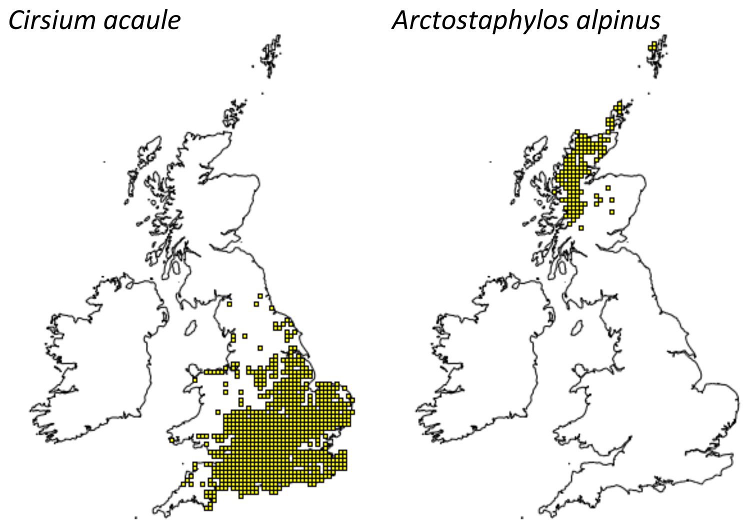


Table 1. Summary of the climate, habitat and disturbance preferences used in the analysis.

Preference indicator	Indicator range	Range for species in dataset	Data source
Mean January temperature of species distribution	-	-1.5 – 4.6°C	Hill et al. 2004, 2007, Pakeman et al. 2022
Mean July temperature of species distribution	-	10.4 – 15.5°C	Hill et al. 2004, 2007, Pakeman et al. 2022
Mean annual precipitation of species distribution	-	808 – 2395	Hill et al. 2004, 2007, Pakeman et al. 2022
Ellenberg F (moisture)	1 – 12	2.0 – 11.9	Tichý et al. 2023
Ellenberg L (light)	1 – 9	1.0 – 9.0	Tichý et al. 2023
Ellenberg N (nitrogen)	1 – 9	1.0 – 8.5	Tichý et al. 2023
Ellenberg R (reaction)	1 – 9	1.0 – 8.1	Tichý et al. 2023
Disturbance severity	0 - 1	0.12 – 0.83	Midolo et al. 2023
Frequency of disturbance	0 - 2.63	0..3 – 2.26	Midolo et al. 2023
Biomass removal by grazing	0 - 1	0.01 – 0.60	Midolo et al. 2023
Biomass removal by soil disturbance	0 - 1	0.01 – 0.75	Midolo et al. 2023

Climate

Temperature

Habitat preferences for most species are close to the mean of the quadrat as climate is one of the controls of species distributions. However, across the five broad habitat classes in the Birse and Robertson dataset it is clear that there is a much higher proportion of species that differ considerably from the mean (Table 2). Nearly 10 % of species, on average, have a temperature preference more than 1°C lower than the mean for January temperature, and 13 % for 1°C for July temperature preferences. Grassland and woodland samples had a much lower proportion of species that have considerably lower temperature refences than the mean, with Moorland and Wetland intermediate in their proportions. Bryophytes of warmer areas have been increasing in occupancy (Pakeman et al. 2022).

Table 2. Average proportion of species per quadrat with climate preferences (January and July temperatures) less than a threshold below the CWM for broad habitats within the Birse and Robertson dataset.

	January				July			
	0.5°C	1°C	1.5°C	2°C	0.5°C	1°C	1.5°C	2°C
Alpine (205)	0.199	0.098	0.037	0.015	0.226	0.133	0.064	0.017
Grassland (562)	0.022	0.011	0.003	0.000	0.035	0.017	0.008	0.001
Moorland (368)	0.092	0.040	0.011	0.005	0.125	0.059	0.017	0.003
Wetland (113)	0.056	0.033	0.015	0.009	0.087	0.043	0.024	0.012
Woodland (263	0.042	0.020	0.006	0.000	0.059	0.020	0.007	0.001

Focussing on a more detailed level of habitat description, National Vegetation Classification communities, a number of habitats are picked out as having a substantial proportion of species that differ considerably from quadrat means (Table 3). For January, H13 (*Calluna vulgaris-Cladonia arbuscula* heathland) and M32 (*Philonotis fontana-Saxifraga stellaris spring*) have more than 10 % of species with a preference more than 1°C lower than the mean, whilst for July, H13, M32, U7 (*Nardus stricta-Carex bigelowii* grass-heath) and U10 (*Carex bigelowii-Racomitrium lanuginosum* moss-heath) all have more than 10 % of species with a preference more than 1°C lower than the mean.

Notably some communities have very few or no species which differ markedly from the mean preference including the mesotrophic grasslands MG6 *Lolium perenne-Cynosurus cristatus* grassland and MG7 *Lolium perenne* leys, as well as U4 *Festuca ovina-Agrostis capillaris-Galium saxatile* grassland and W10 *Quercus robur-Pteridium aquilinum-Rubus fruticosus* woodland.

Table 3. Average proportion of species per quadrat with climate preferences (January and July temperatures) less than a threshold below the CWM for all National Vegetation Communities with 20 or more records in the Birse and Robertson dataset.

	At risk from increased January temperature				At risk from increased July temperature			
	0.5°C	1°C	1.5°C	2°C	0.5°C	1°C	1.5°C	2°C
CG10 (61)	0.040	0.022	0.008	0.000	0.057	0.032	0.014	0.006
CG11(24)	0.076	0.044	0.022	0.003	0.098	0.072	0.037	0.009
H10 (63)	0.064	0.022	0.008	0.001	0.106	0.034	0.013	0.003

H12 (103)	0.090	0.048	0.008	0.005	0.109	0.058	0.012	0.003
H13 (36)	0.336	0.173	0.082	0.022	0.413	0.253	0.100	0.025
H16 (25)	0.134	0.083	0.019	0.006	0.157	0.092	0.041	0.008
H18 (38)	0.102	0.031	0.008	0.003	0.109	0.032	0.015	0.004
H21 (27)	0.093	0.058	0.007	0.000	0.120	0.055	0.007	0.000
M6 (23)	0.029	0.010	0.001	0.001	0.043	0.027	0.008	0.001
M15 (28)	0.027	0.010	0.002	0.002	0.079	0.017	0.003	0.002
M19 (57)	0.121	0.047	0.025	0.014	0.146	0.059	0.029	0.004
M23 (33)	0.018	0.003	0.000	0.000	0.037	0.005	0.000	0.000
M32 (29)	0.142	0.103	0.051	0.036	0.161	0.119	0.072	0.036
MG6 (30)	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000
MG7 (38)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
U4 (176)	0.015	0.009	0.002	0.000	0.032	0.012	0.006	0.001
U5 (81)	0.058	0.033	0.008	0.002	0.074	0.042	0.021	0.002
U6 (26)	0.089	0.050	0.004	0.000	0.088	0.064	0.036	0.000
U7 (48)	0.179	0.085	0.016	0.009	0.193	0.113	0.052	0.012
U10 (35)	0.180	0.059	0.005	0.002	0.191	0.113	0.029	0.002
W10 (26)	0.003	0.000	0.000	0.000	0.013	0.000	0.000	0.000
W11 (62)	0.023	0.012	0.005	0.000	0.052	0.016	0.008	0.000
W17 (24)	0.021	0.012	0.003	0.000	0.038	0.008	0.003	0.000

CG10 *Festuca ovina-Agrostis capillaris-Thymus praecox* grassland (Grassland)
CG11 *Festuca ovina-Agrostis capillaris-Alchemilla alpina* grass-heath (Grassland)
H10 *Calluna vulgaris-Erica cinerea* heath (Moorland)
H12 *Calluna vulgaris-Vaccinium myrtillus* heath (Moorland)
H13 *Calluna vulgaris-Cladonia arbuscula* heath (Alpine, Moorland)
H16 *Calluna vulgaris-Arctostaphylos uva-ursi* heath (Moorland)
H18 *Vaccinium myrtillus-Deschampsia flexuosa* heath (Moorland, Woodland)
H21 *Calluna vulgaris-Vaccinium myrtillus-Sphagnum capillifolium* heath (Moorland, Woodland)
M6 *Carex echinata-Sphagnum recurvum/auriculatum* mire (Grassland)
M15 *Scirpus cespitosus-Erica tetralix* wet heath (Moorland)
M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire (Moorland)
M23 *Juncus effusus/acutiflorus-Galium palustre* rush-pasture (Grassland)
M32 *Philonotis fontana-Saxifraga stellaris* spring (Wetland)
MG6 *Lolium perenne-Cynosurus cristatus* grassland (Grassland)
MG7 *Lolium perenne* leys and related grasslands, *Lolium perenne-Trifolium repens* leys (Grassland)
U4 *Festuca ovina-Agrostis capillaris-Galium saxatile* grassland (Grassland)
U5 *Nardus stricta-Galium saxatile* grassland (Grassland)
U6 *Juncus squarrosus-Festuca ovina* grassland (Grassland)
U7 *Nardus stricta-Carex bigelowii* grass-heath (Alpine)
U10 *Carex bigelowii-Racomitrium lanuginosum* moss-heath (Alpine)
W10 *Quercus robur-Pteridium aquilinum-Rubus fruticosus* woodland (Woodland)
W11 *Quercus petraea-Betula pubescens-Oxalis acetosell*a woodland (Woodland)
W17 *Quercus petraea-Betula pubescens-Dicranum majus* woodland (Woodland)

Rainfall

It is less clear what thresholds to set for rainfall changes compared to likely changes in temperatures predicted for the coming decades. However, as for the temperature analysis, most species have preferences similar to the mean. However, it is clear from Table 4 that there are a higher proportion of species in alpine samples that have sizable differences in habitat preference from the mean.

Table 4. Average proportion of species per quadrat with climate preferences for precipitation lower than the CWM by set thresholds, and hence vulnerable to increased rainfall, and higher than the community weighted by the same thresholds, and hence vulnerable to decreased rainfall, for broad habitats within the Birse and Robertson dataset.

	At risk from increased rainfall			At risk from decreased rainfall		
	100 mm	200 mm	400 mm	100 mm	200 mm	400 mm
Alpine (205)	0.376	0.186	0.026	0.299	0.197	0.096
Grassland (562)	0.056	0.003	0.000	0.062	0.021	0.008
Moorland (368)	0.112	0.005	0.000	0.217	0.078	0.020
Wetland (113)	0.245	0.084	0.000	0.117	0.059	0.025
Woodland (263	0.105	0.013	0.000	0.086	0.034	0.012

Three habitats have a very high proportion of species whose mean rainfall of their distribution is substantially less than the CWM, M32 *Philonotis fontana-Saxifraga stellaris* spring, U7 *Nardus stricta-Carex bigelowii* grass-heath and U10 *Carex bigelowii-Racomitrium lanuginosum* moss-heath, and could, therefore, be at risk if rainfall increased. In addition to H13 *Calluna vulgaris-Cladonia arbuscula* heath, the same three communities also have the highest proportion of species with a mean rainfall of their distribution substantially more than the CWM (Table 5). It is possible that these communities assemble more through the local edaphic conditions than through climate, and contain a set of species with wide climate tolerances. Analysis of trends in abundance for bryophytes suggest that bryophytes of wetter parts of Scotland are declining, whilst those of drier parts are increasing (Pakeman et al. 2022). A similar pattern is seen for lichens.

Table 5. Average proportion of species per quadrat with climate preferences for precipitation lower than the CWM by set thresholds, and hence vulnerable to increased rainfall, and higher than the CWM by the same thresholds, and hence vulnerable to decreased rainfall, for broad habitats within the Birse and Robertson dataset.

	At risk from increased rainfall			At risk from decreased rainfall		
	100 mm	200 mm	400 mm	100 mm	200 mm	400 mm
CG10 (61)	0.057	0.012	0.000	0.095	0.036	0.019
CG11(24)	0.206	0.020	0.000	0.134	0.085	0.039
H10 (63)	0.095	0.000	0.000	0.165	0.070	0.021
H12 (103)	0.050	0.002	0.000	0.184	0.072	0.012
H13 (36)	0.116	0.008	0.000	0.489	0.268	0.118
H16 (25)	0.120	0.009	0.000	0.294	0.107	0.018
H18 (38)	0.218	0.019	0.000	0.158	0.071	0.032
H21 (27)	0.147	0.004	0.000	0.209	0.087	0.033
M6 (23)	0.197	0.028	0.000	0.114	0.029	0.011
M15 (28)	0.179	0.006	0.000	0.187	0.057	0.018

M19 (57)	0.140	0.002	0.000	0.222	0.072	0.018
M23 (33)	0.023	0.003	0.000	0.059	0.011	0.002
M32 (29)	0.505	0.248	0.024	0.203	0.141	0.093
MG6 (30)	0.002	0.000	0.000	0.006	0.001	0.001
MG7 (38)	0.003	0.003	0.000	0.007	0.000	0.000
U4 (176)	0.029	0.000	0.000	0.065	0.014	0.006
U5 (81)	0.135	0.012	0.000	0.096	0.053	0.023
U6 (26)	0.250	0.036	0.000	0.132	0.076	0.048
U7 (48)	0.378	0.130	0.005	0.259	0.170	0.080
U10 (35)	0.543	0.372	0.030	0.219	0.170	0.065
W10 (26)	0.014	0.007	0.000	0.023	0.005	0.003
W11 (62)	0.058	0.004	0.000	0.100	0.032	0.008
W17 (24)	0.198	0.002	0.000	0.100	0.032	0.005

Habitat Preferences

Soil moisture

The Ellenberg moisture indicator provides information on a species' preferred soil moisture niche. It is clear from Table 6 that the habitat type with the highest proportion of species at risk from increases in soil moisture is wetland. It appears that many species depend on drier microsites in wetlands, and these may be at risk from increased rainfall or wetland restoration. Conversely, wetlands appeared least at risk of losing species under conditions of increased dryness. Instead, alpine, grassland and, especially, heathland contain species whose preference for damper niches put them at risk of loss if warmer temperatures reduce soil moisture. Analysis of trends in abundance for bryophytes suggest that bryophytes of wetter habitats are declining, whilst those of drier habitats are increasing (Pakeman et al. 2022). Vascular plants have seen the biggest declines in species of both dry and wet sites (Stroh et al. 2023).

Table 6. Average proportion of species per quadrat with habitat preferences for moisture lower than the CWM by set thresholds, and hence vulnerable to increased rainfall, and higher than the CWM by the same thresholds, and hence vulnerable to decreased rainfall, for broad habitats within the Birse and Robertson dataset. Ellenberg's moisture indicator has a scale of 1 to 12.

	At risk from increased moisture			At risk from decreased moisture		
	0.5	1	2	0.5	1	2
Alpine (205)	0.268	0.142	0.051	0.315	0.179	0.070
Grassland (562)	0.346	0.192	0.045	0.316	0.220	0.064
Moorland (368)	0.316	0.181	0.059	0.285	0.195	0.080
Wetland (113)	0.365	0.263	0.120	0.257	0.126	0.013
Woodland (263)	0.216	0.074	0.006	0.238	0.098	0.020

As might be expected from the habitat level analysis, the wetland community have high proportions of species at risk from increased soil moisture (Table 7) as the five communities with the highest proportion of species more than one Ellenberg F unit from the CWM were the five mire communities

(M). They also made up five of the six communities with the highest proportion of species more than two units from the mean. The community that edged into this later list was H13 *Calluna vulgaris-Cladonia arbuscula* heath.

The communities with the most species more than one unit higher than the CWM were from a mix of habitats including CG11 *Festuca ovina-Agrostis capillaris-Alchemilla alpina* grass-heath, M15 *Scirpus cespitosus-Erica tetralix* wet heath, M19*Calluna vulgaris-Eriophorum vaginatum* blanket mire, MG6 *Lolium perenne-Cynosurus cristatus* grassland and U4 *Festuca ovina-Agrostis capillaris-Galium saxatile* grassland. The two mire communities and the calcareous grassland (CG) were the three with the most species that had Ellenberg F scores more than two units above the CWM. Both M15 and M19 contain a high number of species differing considerably from the community weighted mean, possibly indicating the role of microtopography in determining their species richness, but it does suggest the potential for species loss under changing conditions.

Table 7. Average proportion of species per quadrat with climate preferences for precipitation lower than the CWM by set thresholds, and hence vulnerable to increased rainfall, and higher than the community weighted by the same thresholds, and hence vulnerable to decreased rainfall, for broad habitats within the Birse and Robertson dataset. Ellenberg's moisture indicator has a scale of 1 to 12.

	At risk from increased moisture			At risk from decreased moisture		
	0.5	1	2	0.5	1	2
CG10 (61)	0.332	0.173	0.045	0.298	0.217	0.090
CG11 (24)	0.392	0.215	0.045	0.326	0.240	0.110
H10 (63)	0.303	0.127	0.016	0.291	0.210	0.093
H12 (103)	0.160	0.032	0.004	0.242	0.138	0.050
H13 (36)	0.338	0.234	0.113	0.146	0.111	0.083
H16 (25)	0.187	0.088	0.018	0.274	0.171	0.086
H18 (38)	0.150	0.056	0.003	0.289	0.103	0.025
H21 (27)	0.165	0.042	0.002	0.338	0.120	0.032
M6 (23)	0.435	0.327	0.151	0.315	0.197	0.039
M15 (28)	0.412	0.272	0.126	0.346	0.244	0.095
M19 (57)	0.518	0.396	0.085	0.325	0.257	0.118
M23 (33)	0.383	0.271	0.112	0.339	0.206	0.035
M32 (29)	0.424	0.330	0.169	0.251	0.108	0.005
MG6 (30)	0.324	0.162	0.034	0.406	0.293	0.083
MG7 (38)	0.348	0.211	0.046	0.293	0.169	0.017
U4 (176)	0.337	0.158	0.019	0.314	0.244	0.073
U5 (81)	0.370	0.167	0.017	0.276	0.210	0.076
U6 (26)	0.276	0.120	0.014	0.303	0.155	0.036
U7 (48)	0.282	0.105	0.019	0.298	0.161	0.050
U10 (35)	0.158	0.070	0.018	0.420	0.195	0.048
W10 (26)	0.203	0.064	0.000	0.210	0.070	0.015
W11 (62)	0.304	0.089	0.000	0.230	0.109	0.009
W17 (24)	0.160	0.030	0.000	0.220	0.078	0.009

Light

The habitats with the highest proportion of species with a light indicator score more than one unit or two units lower than the CWM were alpine and moorland (Table 8). In contrast woodlands had the highest proportion of species more with light scores higher than the CWM indicating a substantial number of species at risk from denser canopies and less disturbance. In general, a greater proportion of species had light scores lower than the CWM than higher. This is likely because community dominants in the open habitat are more light-demanding than the subordinate species exploiting gaps between the dominants. Bryophytes with low Ellenberg indicator values are, on average, doing better than those characteristic of open areas (Pakeman et al. 2022). A similar pattern is seen with vascular plants (Stroh et al. 2022).

Table 8. Average proportion of species per quadrat with habitat preferences for light lower than the CWM by set thresholds, and hence vulnerable to increased light, and higher than the CWM by the same thresholds, and hence vulnerable to decreased light, for broad habitats within the Birse and Robertson dataset. Ellenberg's light indicator has a scale from 1 to 9.

	At risk from increased light			At risk from decreased light		
	0.5	1	2	0.5	1	2
Alpine (205)	0.433	0.296	0.059	0.258	0.087	0.003
Grassland (562)	0.293	0.142	0.035	0.229	0.058	0.001
Moorland (368)	0.429	0.273	0.073	0.265	0.072	0.003
Wetland (113)	0.255	0.097	0.022	0.226	0.060	0.002
Woodland (263)	0.311	0.193	0.052	0.282	0.155	0.018

The communities with the most species with light scores more than one unit below the CWM included H13 *Calluna vulgaris-Cladonia arbuscula* heath, H21 *Calluna vulgaris-Vaccinium myrtillus-Sphagnum capillifolium* heath, M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire, U6 *Juncus squarrosus-Festuca ovina* grassland and U7 *Nardus stricta-Carex bigelowii* grass-heath, with H21, M19 and U6 the top three with the highest proportions of species more than two units below the CWM (Table 9). These habitats might be most sensitive to the loss of the community dominants or increased levels of grazing or other disturbance.

The communities with the most species with light scores less than the CWM included the three woodland communities as well as H18 *Vaccinium myrtillus-Deschampsia flexuosa* heath and M32 *Philonotis fontana-Saxifraga stellaris* spring. These communities appear to be the ones at risk from reduced levels of disturbance.

Table 9. Average proportion of species per quadrat with habitat preferences for light lower than the CWM by set thresholds, and hence vulnerable to increased light, and higher than the CWM by the same thresholds, and hence vulnerable to decreased light, for broad habitats within the Birse and Robertson dataset. Ellenberg's light indicator has a scale from 1 to 9.

	At risk from increased light			At risk from decreased light		
	0.5	1	2	0.5	1	2
CG10 (61)	0.253	0.130	0.030	0.285	0.058	0.001
CG11 (24)	0.287	0.148	0.029	0.321	0.115	0.003
H10 (63)	0.386	0.254	0.054	0.272	0.039	0.000
H12 (103)	0.512	0.258	0.061	0.249	0.105	0.003
H13 (36)	0.421	0.365	0.044	0.185	0.045	0.000

H16 (25)	0.465	0.218	0.042	0.298	0.122	0.000
H18 (38)	0.301	0.134	0.031	0.305	0.205	0.020
H21 (27)	0.503	0.326	0.108	0.228	0.114	0.000
M6 (23)	0.343	0.164	0.048	0.215	0.038	0.000
M15 (28)	0.283	0.178	0.069	0.351	0.079	0.000
M19 (57)	0.449	0.368	0.136	0.301	0.075	0.004
M23 (33)	0.357	0.192	0.057	0.181	0.049	0.004
M32 (29)	0.215	0.106	0.022	0.378	0.169	0.009
MG6 (30)	0.307	0.146	0.032	0.164	0.018	0.000
MG7 (38)	0.368	0.184	0.033	0.097	0.008	0.000
U4 (176)	0.261	0.117	0.029	0.235	0.051	0.001
U5 (81)	0.384	0.220	0.053	0.237	0.082	0.000
U6 (26)	0.494	0.335	0.121	0.246	0.099	0.002
U7 (48)	0.487	0.326	0.062	0.251	0.099	0.004
U10 (35)	0.440	0.255	0.050	0.279	0.099	0.003
W10 (26)	0.367	0.221	0.053	0.317	0.155	0.017
W11 (62)	0.290	0.208	0.059	0.333	0.183	0.029
W17 (24)	0.285	0.176	0.066	0.334	0.167	0.027

Nitrogen

Alpine and moorland habitats had the lowest proportion of species differing by more than one or two units in either direction from the CWM (Table 10). The other habitats had quite high numbers of species differing from the CWM, especially in terms of a risk from reduced nitrogen. This pattern might be because alpine and moorland systems may have lost their most sensitive species and that the other habitats contain many species adapted to relatively higher levels of nitrogen than the community dominants. Vascular plants of low fertility sites are declining faster than those of more fertile places (Stroh et al. 2023). Bryophytes characteristic of high nitrogen sites are increasing in occupancy (Pakeman et al. 2022).

Table 10. Average proportion of species per quadrat with habitat preferences for nitrogen lower than the CWM by set thresholds, and hence vulnerable to increased nitrogen and higher than the CWM by the same thresholds, and hence vulnerable to decreased nitrogen, for broad habitats within the Birse and Robertson dataset. Ellenberg's nitrogen indicator has a scale from 1 to 9.

	At risk from increased nitrogen			At risk from decreased nitrogen		
	0.5	1	2	0.5	1	2
Alpine (205)	0.263	0.093	0.003	0.283	0.137	0.029
Grassland (562)	0.305	0.149	0.025	0.328	0.211	0.076
Moorland (368)	0.119	0.011	0.000	0.296	0.115	0.024
Wetland (113)	0.303	0.160	0.039	0.315	0.218	0.099
Woodland (263)	0.299	0.136	0.018	0.305	0.197	0.068

The communities with the highest proportion of species more than one unit less than the CWM included some of the most fertile communities, including the agricultural grasslands MG6 *Lolium perenne-Cynosurus cristatus* grassland and MG7 *Lolium perenne* leys, the most productive acid grassland U4 *Festuca ovina-Agrostis capillaris-Galium saxatile* grassland and one of the more productive mire communities M23 *Juncus effusus/acutiflorus-Galium palustre* rush-pasture, as well as the woodland W11 *Quercus petraea-Betula pubescens-Oxalis acetosell*a woodland (Table 11). MG6 and MG7 were the two communities with the highest proportion of species more than two units less than the CWM. Potentially, there species persisting in these habitats that could be at risk from increased levels of fertiliser application.

A higher proportion of species had scores more than one or two units higher than the CWM than lower, suggesting many subordinate species may be characterised by higher nutrient requirements than the dominants. The highest proportions of these species occurred in much of the same communities with species at risk of increased nitrogen, namely M23, MG6, U4 and W11 as well as W10 *Quercus robur-Pteridium aquilinum-Rubus fruticosus* woodland. These habitats appear most at risk from reduced agricultural inputs and/or reduced atmospheric deposition.

Table 11. Average proportion of species per quadrat with habitat preferences for nitrogen lower than the CWM by set thresholds, and hence vulnerable to increased nitrogen and higher than the CWM by the same thresholds, and hence vulnerable to decreased nitrogen, for broad habitats within the Birse and Robertson dataset. Ellenberg's nitrogen indicator has a scale from 1 to 9.

	At risk from increased nitrogen			At risk from decreased nitrogen		
	0.5	1	2	0.5	1	2
CG10 (61)	0.351	0.113	0.003	0.291	0.206	0.078
CG11 (24)	0.235	0.056	0.000	0.282	0.162	0.065
H10 (63)	0.113	0.012	0.000	0.360	0.205	0.048
H12 (103)	0.089	0.005	0.000	0.291	0.122	0.022
H13 (36)	0.233	0.000	0.000	0.272	0.117	0.063
H16 (25)	0.153	0.000	0.000	0.269	0.156	0.021
H18 (38)	0.181	0.059	0.000	0.188	0.088	0.018
H21 (27)	0.115	0.011	0.000	0.295	0.140	0.031
M6 (23)	0.231	0.066	0.000	0.273	0.202	0.088
M15 (28)	0.188	0.005	0.000	0.191	0.074	0.017
M19 (57)	0.110	0.000	0.000	0.350	0.061	0.015
M23 (33)	0.355	0.224	0.009	0.436	0.312	0.132
M32 (29)	0.322	0.130	0.006	0.330	0.185	0.086
MG6 (30)	0.389	0.281	0.099	0.386	0.255	0.072
MG7 (38)	0.364	0.267	0.073	0.231	0.118	0.033
U4 (176)	0.346	0.166	0.019	0.330	0.226	0.086
U5 (81)	0.179	0.031	0.000	0.280	0.126	0.026
U6 (26)	0.116	0.030	0.000	0.270	0.094	0.005
U7 (48)	0.222	0.122	0.000	0.278	0.124	0.017
U10 (35)	0.242	0.099	0.000	0.347	0.167	0.025
W10 (26)	0.302	0.165	0.032	0.423	0.281	0.100
W11 (62)	0.363	0.187	0.017	0.324	0.218	0.088
W17 (24)	0.272	0.074	0.000	0.286	0.176	0.081

Reaction (soil pH)

As for nitrogen, alpine and moorlands contain the fewest species at risk from increased pH, whereas grasslands, wetlands and woodlands contain more species with Ellenberg reaction scores less than the CWM (Table 12). Increased soil pH may arise during recovery from acidification or, in agricultural systems, from the application of lime. In contrast, risks from decreased soil pH may stem from continued acidic deposition or, again in agricultural systems, from the cessation of lime application. Species at risk appear concentrated in grasslands, moorlands and woodlands. Lichens characteristic of more acidic sites are decreasing (Pakeman et al. 2022). In contrast declines in vascular plant species of base-rich habitats have seen the steepest declines in occupancy (Stroh et al. 2023).

Table 12. Average proportion of species per quadrat with habitat preferences for soil reaction lower than the CWM by set thresholds, and hence vulnerable to increased pH, and higher than the CWM by the same thresholds, and hence vulnerable to decreased pH, for broad habitats within the Birse and Robertson dataset. Ellenberg's reaction indicator has a scale from 1 to 9.

	At risk from increased pH			At risk from decreased pH		
	0.5	1	2	0.5	1	2
Alpine (205)	0.134	0.043	0.017	0.301	0.153	0.040
Grassland (562)	0.322	0.206	0.062	0.386	0.255	0.092
Moorland (368)	0.141	0.036	0.003	0.279	0.212	0.090
Wetland (113)	0.311	0.194	0.055	0.320	0.202	0.065
Woodland (263)	0.382	0.237	0.059	0.359	0.251	0.099

The communities with the highest proportion of specie at risk from increased pH include the calcareous grasslands CG10 *Festuca ovina-Agrostis capillaris-Thymus praecox* grassland and CG11 *Festuca ovina-Agrostis capillaris-Alchemilla alpina* grass-heath as well as U4 *Festuca ovina-Agrostis capillaris-Galium saxatile* grassland, W11 *Quercus petraea-Betula pubescens-Oxalis acetosell*a woodland and W17 *Quercus petraea-Betula pubescens-Dicranum majus* woodland (Table 13). The high numbers of species in these communities may reflect the dependence of some species on more acidic microsites with this communities, for instance where soil organic matter has built up.

Across all the communities, more species are at risk from decreased pH than increased pH. The communities that show the highest proportion of species more than one reaction unit more than the CWM include some of the above communities CG11, U4 and W17, but also H10 *Calluna vulgaris-Erica cinerea* heath and M6 *Carex echinata-Sphagnum recurvum/auriculatum* mire. However, 10 of the 23 communities have more than 10 % of species with a reaction score more than two units higher than the CWM, suggesting many species at risk from continued acidification.

Table 13. Average proportion of species per quadrat with climate preferences for precipitation lower than the CWM by set thresholds, and hence vulnerable to increased pH, and higher than the CWM by the same thresholds, and hence vulnerable to decreased pH, for broad habitats within the Birse and Robertson dataset. Ellenberg's reaction indicator has a scale from 1 to 9.

	At risk from increased pH			At risk from decreased pH		
	0.5	1	2	0.5	1	2
CG10 (61)	0.365	0.288	0.129	0.394	0.271	0.095
CG11 (24)	0.382	0.264	0.078	0.450	0.355	0.169
H10 (63)	0.177	0.077	0.019	0.403	0.295	0.141
H12 (103)	0.110	0.023	0.003	0.295	0.217	0.093

H13 (36)	0.022	0.000	0.000	0.279	0.178	0.084
H16 (25)	0.082	0.011	0.000	0.336	0.284	0.119
H18 (38)	0.386	0.177	0.002	0.296	0.196	0.087
H21 (27)	0.410	0.112	0.000	0.278	0.211	0.072
M6 (23)	0.333	0.207	0.046	0.393	0.313	0.140
M15 (28)	0.190	0.072	0.004	0.315	0.238	0.107
M19 (57)	0.164	0.030	0.000	0.196	0.143	0.051
M23 (33)	0.310	0.196	0.041	0.457	0.282	0.071
M32 (29)	0.277	0.153	0.052	0.384	0.276	0.113
MG6 (30)	0.167	0.119	0.021	0.331	0.131	0.012
MG7 (38)	0.253	0.062	0.044	0.129	0.020	0.004
U4 (176)	0.335	0.248	0.082	0.445	0.306	0.104
U5 (81)	0.358	0.162	0.018	0.339	0.252	0.126
U6 (26)	0.170	0.043	0.000	0.303	0.232	0.095
U7 (48)	0.113	0.002	0.000	0.260	0.135	0.031
U10 (35)	0.056	0.020	0.008	0.346	0.138	0.017
W10 (26)	0.287	0.163	0.019	0.425	0.284	0.110
W11 (62)	0.304	0.089	0.000	0.230	0.109	0.009
W17 (24)	0.160	0.030	0.000	0.220	0.078	0.009

Disturbance

Disturbance severity

Alpine and moorland habitats appear to have higher number of species whose disturbance severity indicator is more than 0.1 or 0.2 units less than the CWM, suggesting these habitats have a number of species that would be at risk if levels of disturbance increased (Table 14). However, alpine habitats also have the highest proportion of species where their indicator value was substantially higher than the CWM. Grasslands had very low proportions of species that differed by large degree from the CWM, suggesting these more heavily grazed habitats largely contain species adapted to similar levels of disturbance to the community dominants.

Table 14. Average proportion of species per quadrat with preferences for disturbance severity lower than the CWM by set thresholds, and hence vulnerable to increased disturbance severity, and higher than the CWM by the same thresholds, and hence vulnerable to decreased disturbance severity, for broad habitats within the Birse and Robertson dataset. Disturbance severity has a possible range of 0 to 1, but the occupied scale is 0.10 to 0.96.

	At risk from increased severity			At risk from decreased severity		
	0.05	0.1	0.2	0.05	0.1	0.2
Alpine (205)	0.305	0.202	0.042	0.432	0.310	0.073
Grassland (562)	0.175	0.066	0.009	0.257	0.109	0.010
Moorland (368)	0.338	0.188	0.045	0.323	0.203	0.015
Wetland (113)	0.271	0.145	0.029	0.375	0.202	0.036
Woodland (263)	0.219	0.107	0.007	0.242	0.075	0.002

The communities with the highest proportion of species at risk from increased severity of disturbance were the mire communities M15 *Scirpus cespitosus-Erica tetralix* wet heath, M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire and M32 *Philonotis fontana-Saxifraga stellaris* spring judged at a 0.1 difference from the CWM, but at a threshold of 0.2 it was H16 *Calluna vulgaris-Arctostaphylos uva-ursi* heath, M15 and U10 *Carex bigelowii-Racomitrium lanuginosum* moss-heath (Table 15). These communities contain relatively high numbers of species that could be lost if levels of disturbance increased.

The communities that contain the highest proportion of species with disturbance indicator values more than 0.1 above the CWM included a number of heathlands and upland grasslands including H12 *Calluna vulgaris-Vaccinium myrtillus* heath, H16 *Calluna vulgaris-Arctostaphylos uva-ursi* heath, U6 *Juncus squarrosus-Festuca ovina* grassland, U7 *Nardus stricta-Carex bigelowii* grass-heath and U10 *Carex bigelowii-Racomitrium lanuginosum* moss-heath, with U6 an U& showing the highest proportions with a threshold of 0.2. These habitats would likely lose species if disturbance levels decreased.

Table 15. Average proportion of species per quadrat with preferences for disturbance severity lower than the CWM by set thresholds, and hence vulnerable to increased disturbance severity, and higher than the CWM by the same thresholds, and hence vulnerable to decreased disturbance severity, for broad habitats within the Birse and Robertson dataset. Disturbance severity has a possible range of 0 to 1, but the occupied scale is 0.10 to 0.96.

	At risk from increased severity			At risk from decreased severity		
	0.05	0.1	0.2	0.05	0.1	0.2
CG10 (61)	0.179	0.066	0.003	0.222	0.108	0.002
CG11 (24)	0.260	0.121	0.019	0.373	0.178	0.019
H10 (63)	0.279	0.121	0.056	0.258	0.148	0.003
H12 (103)	0.254	0.128	0.029	0.369	0.246	0.002
H13 (36)	0.406	0.191	0.052	0.298	0.200	0.000
H16 (25)	0.294	0.157	0.086	0.328	0.254	0.000
H18 (38)	0.348	0.175	0.036	0.258	0.097	0.000
H21 (27)	0.204	0.087	0.014	0.434	0.213	0.000
M15 (28)	0.406	0.276	0.069	0.288	0.143	0.020
M19 (57)	0.502	0.275	0.031	0.307	0.194	0.032
M23 (33)	0.219	0.073	0.009	0.258	0.079	0.001
M32 (29)	0.356	0.272	0.053	0.365	0.198	0.022
M6 (23)	0.257	0.096	0.012	0.319	0.148	0.025
MG6 (30)	0.098	0.036	0.018	0.164	0.055	0.005
MG7 (38)	0.089	0.012	0.008	0.168	0.069	0.007
U10 (35)	0.275	0.212	0.067	0.558	0.374	0.060
U4 (176)	0.146	0.045	0.005	0.212	0.080	0.003
U5 (81)	0.211	0.112	0.020	0.417	0.231	0.035
U6 (26)	0.204	0.087	0.010	0.551	0.378	0.138
U7 (48)	0.263	0.180	0.033	0.423	0.314	0.091
W10 (26)	0.163	0.063	0.000	0.185	0.009	0.000

W11 (62)	0.266	0.157	0.005	0.296	0.069	0.000
W17 (24)	0.286	0.143	0.000	0.291	0.074	0.000

Disturbance frequency

Alpine and grassland habitats appear to have higher number of species whose disturbance frequency indicator is more than 0.1 or 0.2 units less than the CWM, suggesting these habitats have a number of species that would be at risk if the frequency of disturbance increased (Table 16). In contrast moorland habitats also have the highest proportion of species where their indicator value was substantially higher than the CWM, suggesting that this group of habitats has the highest proportion of species at risk from reduced disturbance frequencies.

Table 16. Average proportion of species per quadrat with preferences for the frequency of disturbance than the CWM by set thresholds, and hence vulnerable to increased disturbance frequency, and higher than the CWM by the same thresholds, and hence vulnerable to decreased disturbance frequency l, for broad habitats within the Birse and Robertson dataset. The range of disturbance frequencies shown by species is 0 (one every hundred years) to 2.63 (c. four times a year).

	At risk from increased frequency			At risk from decreased frequency		
	0.1	0.2	0.4	0.1	0.2	0.4
Alpine (205)	0.480	0.423	0.263	0.356	0.276	0.166
Grassland (562)	0.410	0.332	0.201	0.399	0.300	0.153
Moorland (368)	0.341	0.259	0.059	0.406	0.344	0.244
Wetland (113)	0.327	0.210	0.098	0.379	0.282	0.146
Woodland (263)	0.343	0.202	0.063	0.272	0.225	0.133

The communities with the highest proportion of species at risk from increased frequency of disturbance were a range of upland and alpine grasslands in particular U6 *Juncus squarrosus-Festuca ovina* grassland, U7 *Nardus stricta-Carex bigelowii* grass-heath and U10 *Carex bigelowii-Racomitrium lanuginosum* moss-heath. However, a range of other grasslands scored nearly as highly including upland calcareous grasslands (CG10, CG11) and the main matrotrophic grasslands (MG6, MG7).

The communities with the most species at risk from reduced disturbance were heath and mire communities including the upland dry heath communities H10 *Calluna vulgaris-Erica cinerea* heath and H16 *Calluna vulgaris-Arctostaphylos uva-ursi* heath, the wet heath community M15 *Scirpus cespitosus-Erica tetralix* and the blanket bog community M19 *Calluna vulgaris-Eriophorum vaginatum*. These habitats are usually thought to benefit from low frequencies of disturbance; however, a lack of disturbance may lead to the community dominants shading out other species (Lee et al. 2013).

Table 17. Average proportion of species per quadrat with preferences for the frequency of disturbance lower than the CWM by set thresholds, and hence vulnerable to increased disturbance frequency l, and higher than the CWM by the same thresholds, and hence vulnerable to decreased disturbance frequency, for broad habitats within the Birse and Robertson dataset. The range of disturbance frequencies shown by species is 0 (one every hundred years) to 2.63 (c. four times a year).

	At risk from increased frequency			At risk from decreased frequency		
	0.1	0.2	0.4	0.1	0.2	0.4

CG10 (61)	0.383	0.316	0.205	0.442	0.351	0.212
CG11 (24)	0.404	0.334	0.246	0.411	0.333	0.169
H10 (63)	0.321	0.253	0.066	0.461	0.416	0.294
H12 (103)	0.425	0.324	0.044	0.332	0.256	0.207
H13 (36)	0.348	0.315	0.019	0.273	0.217	0.170
H16 (25)	0.346	0.312	0.009	0.326	0.300	0.282
H18 (38)	0.307	0.179	0.061	0.407	0.364	0.197
H21 (27)	0.495	0.306	0.009	0.256	0.135	0.099
M15 (28)	0.270	0.190	0.069	0.613	0.512	0.310
M19 (57)	0.274	0.173	0.048	0.397	0.365	0.305
M23 (33)	0.474	0.371	0.189	0.337	0.231	0.103
M32 (29)	0.308	0.211	0.107	0.450	0.336	0.214
M6 (23)	0.444	0.326	0.216	0.318	0.211	0.080
MG6 (30)	0.490	0.414	0.251	0.370	0.271	0.121
MG7 (38)	0.518	0.443	0.296	0.266	0.164	0.077
U10 (35)	0.526	0.467	0.338	0.343	0.282	0.209
U4 (176)	0.372	0.296	0.165	0.428	0.324	0.171
U5 (81)	0.437	0.383	0.269	0.392	0.267	0.080
U6 (26)	0.487	0.430	0.328	0.371	0.257	0.037
U7 (48)	0.516	0.448	0.342	0.329	0.213	0.106
W10 (26)	0.285	0.145	0.037	0.198	0.167	0.122
W11 (62)	0.498	0.326	0.103	0.298	0.268	0.189
W17 (24)	0.346	0.145	0.036	0.278	0.241	0.150

Grazing

It is grassland and wetland habitats that harbour the most species that differ substantially from the CWM in both directions in terms of their grazing indicator (Table 20). This suggests that there is considerable potential for species loss if management is altered in any direction. Woodland and moorland habitats have very few species that differ substantially from the CWM suggesting they may see few species losses if grazing management were to be changed.

Table 20. Average proportion of species per quadrat with preferences for grazing severity lower than the CWM by set thresholds, and hence vulnerable to increased grazing, and higher than the CWM by the same thresholds, and hence vulnerable to decreased grazing, for broad habitats within the Birse and Robertson dataset. The range of the severity of grazing has a possible range of 0 to 1, but the occupied scale runs from 0 to 0.94 of aboveground biomass removed by grazing.

	At risk from increased grazing			At risk from decreased grazing		
	0.05	0.1	0.2	0.05	0.1	0.2
Alpine (205)	0.133	0.018	0.002	0.068	0.007	0.001
Grassland (562)	0.220	0.056	0.003	0.116	0.044	0.003
Moorland (368)	0.128	0.007	0.000	0.102	0.014	0.000
Wetland (113)	0.209	0.073	0.001	0.256	0.116	0.014
Woodland (263)	0.031	0.002	0.000	0.074	0.014	0.001

Three communities stand out in respect to the proportion of species susceptible to increased grazing at a threshold of 0.1 units below the CWM: M32 *Philonotis fontana-Saxifraga stellaris* spring, MG6 *Lolium perenne-Cynosurus cristatus* grassland and MG7 *Lolium perenne* leys (Table 21). The latter two are surprising as they are the two communities that are subject to the highest levels of grazing due to their productivity. Possibly the subordinate species in these habitats are less tolerant of grazing than the dominants. However, M32 is a bryophyte dominated spring community at moderate to high altitudes whose composition is thought to be more determined by climate rather than grazing. However, it may be that they remain open due to disturbance by animals. Little is known about how this community responds to management, so it is possible that this widespread of grazing indicators within the community is a reflection of the dominance of other drivers in determining composition.

M32 also shows up as the community with the highest proportion of species at risk from decreased grazing by having a grazing score more than 0.1 bigger than the CWM. Other communities with high proportions of species include MG6 but also CG10 *Festuca ovina-Agrostis capillaris-Thymus praecox* grassland and U4 *Festuca ovina-Agrostis capillaris-Galium saxatile* grassland, both of which are preferred communities for grazers in upland areas. This suggests that these communities may see declines in some species if grazing is reduced in the uplands.

Across all habitats, very few species differed substantially from the CWM. This implies that grazing is quite a strong filter on the presence or absence of different plant species compared to other drivers of species composition.

Table 21. Average proportion of species per quadrat with preferences for grazing severity lower than the CWM by set thresholds, and hence vulnerable to increased grazing, and higher than the CWM by the same thresholds, and hence vulnerable to decreased grazing, for broad habitats within the Birse and Robertson dataset. The range of the severity of grazing has a possible range of 0 to 1, but the occupied scale runs from 0 to 0.94 of aboveground biomass removed by grazing.

	At risk from increased grazing			At risk from decreased grazing		
	0.05	0.1	0.2	0.05	0.1	0.2
CG10 (61)	0.174	0.014	0.000	0.108	0.055	0.000
CG11 (24)	0.181	0.028	0.000	0.094	0.024	0.001
H10 (63)	0.120	0.004	0.000	0.063	0.008	0.000
H12 (103)	0.059	0.003	0.000	0.057	0.010	0.000
H13 (36)	0.054	0.000	0.000	0.011	0.000	0.000
H16 (25)	0.135	0.000	0.000	0.048	0.012	0.000
H18 (38)	0.030	0.002	0.000	0.127	0.002	0.000
H21 (27)	0.043	0.000	0.000	0.054	0.007	0.000
M15 (28)	0.143	0.008	0.000	0.182	0.041	0.000
M19 (57)	0.230	0.000	0.000	0.143	0.012	0.000
M23 (33)	0.265	0.035	0.001	0.143	0.039	0.003
M32 (29)	0.274	0.101	0.000	0.314	0.126	0.005
M6 (23)	0.215	0.028	0.000	0.129	0.024	0.000
MG6 (30)	0.461	0.202	0.008	0.151	0.058	0.009
MG7 (38)	0.458	0.233	0.034	0.131	0.041	0.009
U10 (35)	0.062	0.000	0.000	0.100	0.005	0.001
U4 (176)	0.186	0.035	0.000	0.108	0.046	0.001

U5 (81)	0.165	0.022	0.000	0.052	0.012	0.000
U6 (26)	0.176	0.019	0.000	0.019	0.006	0.000
U7 (48)	0.206	0.013	0.000	0.027	0.000	0.000
W10 (26)	0.000	0.000	0.000	0.067	0.016	0.000
W11 (62)	0.019	0.000	0.000	0.096	0.006	0.000
W17 (24)	0.007	0.000	0.000	0.108	0.009	0.000

Soil disturbance

Grasslands are the habitat with the highest proportion of species at risk from increased soil disturbance (Table 22) suggesting that these habitats harbour species that are poor at regenerating after soil disturbance. All habitats had much higher proportions of species at risk of decreased soil disturbance, with the highest proportions in wetlands. Many species may only persist through the maintenance of regeneration niches through soil disturbance.

Table 22. Average proportion of species per quadrat with preferences for soil disturbance lower than the CWM by set thresholds, and hence vulnerable to increased soil disturbance, and higher than the CWM by the same thresholds, and hence vulnerable to decreased soil disturbance, for broad habitats within the Birse and Robertson dataset. Soil disturbance is disturbance that causes loss of plant biomass from soil turning or ploughing. It has a possible range of 0 to 1, but an occupied scale of 0 to 0.94.

	At risk from increased soil disturbance			At risk from decreased soil disturbance		
	0.05	0.1	0.2	0.05	0.1	0.2
Alpine (205)	0.149	0.015	0.000	0.119	0.052	0.000
Grassland (562)	0.213	0.051	0.001	0.230	0.075	0.005
Moorland (368)	0.034	0.002	0.000	0.079	0.031	0.000
Wetland (113)	0.130	0.011	0.000	0.188	0.097	0.014
Woodland (263)	0.090	0.011	0.000	0.145	0.070	0.003

The four communities with the highest proportion of species at risk of decreased soil disturbance are communities that are subject to relatively high levels of grazing, either through high stocking rates on enclosed land, MG6 *Lolium perenne-Cynosurus cristatus* grassland and MG7 *Lolium perenne* leys, or as highly preferred grazing in unenclosed situations, CG10 *Festuca ovina-Agrostis capillaris-Thymus praecox* grassland and U4 *Festuca ovina-Agrostis capillaris-Galium saxatile* grassland (Table 23). The presence of MG7 in the list is surprising given the frequent need to reseed *Lolium perenne* leys to maintain its presence in the sward. For the other grasslands it suggests that some of the species present are poor at regenerating after soil disturbance.

Communities with a high proportion of species more than 0.1 units higher than the CWM include M23 *Juncus effusus/acutiflorus-Galium palustre* rush-pasture and M32 *Philonotis fontana-Saxifraga stellaris* spring, as well as CG10 and MG6.

Table 23. Average proportion of species per quadrat with preferences for soil disturbance lower than the CWM by set thresholds, and hence vulnerable to increased soil disturbance, and higher than the CWM by the same thresholds, and hence vulnerable to decreased soil disturbance, for broad habitats within the Birse and Robertson dataset. Soil disturbance is disturbance that causes loss of plant

biomass from soil turning or ploughing. It has a possible range of 0 to 1, but an occupied scale of 0 to 0.94.

	At risk from increased soil disturbance			At risk from decreased soil disturbance		
	0.05	0.1	0.2	0.05	0.1	0.2
CG10 (61)	0.270	0.028	0.000	0.248	0.088	0.002
CG11 (24)	0.201	0.021	0.000	0.226	0.080	0.001
H10 (63)	0.054	0.002	0.000	0.154	0.056	0.000
H12 (103)	0.020	0.000	0.000	0.090	0.044	0.001
H13 (36)	0.126	0.025	0.000	0.000	0.000	0.000
H16 (25)	0.045	0.000	0.000	0.055	0.023	0.000
H18 (38)	0.042	0.000	0.000	0.187	0.071	0.000
H21 (27)	0.008	0.000	0.000	0.047	0.013	0.000
M15 (28)	0.025	0.003	0.000	0.078	0.015	0.000
M19 (57)	0.007	0.000	0.000	0.018	0.009	0.000
M23 (33)	0.134	0.004	0.000	0.329	0.160	0.009
M32 (29)	0.177	0.019	0.000	0.224	0.124	0.012
M6 (23)	0.066	0.016	0.000	0.197	0.107	0.006
MG6 (30)	0.324	0.129	0.000	0.159	0.050	0.008
MG7 (38)	0.356	0.139	0.004	0.173	0.078	0.011
U10 (35)	0.115	0.000	0.000	0.187	0.077	0.000
U4 (176)	0.255	0.070	0.000	0.202	0.037	0.004
U5 (81)	0.117	0.006	0.000	0.224	0.052	0.002
U6 (26)	0.021	0.000	0.000	0.218	0.064	0.000
U7 (48)	0.208	0.004	0.000	0.132	0.067	0.000
W10 (26)	0.167	0.025	0.000	0.162	0.074	0.010
W11 (62)	0.170	0.019	0.000	0.196	0.084	0.001
W17 (24)	0.043	0.000	0.000	0.132	0.068	0.005

Next steps

For the climate preferences it is relatively straightforward to choose appropriate thresholds against which to judge the species as predictions of climate change are available. However, the other preferences thresholds have been set in relation to the range for each indicator and may be less informative as it is not known whether they are set too optimistically or pessimistically.

A range of next steps are planned for this data:

- Use the climate preference scores to assess vulnerability of selected habitat types and/or vegetation communities to the exposure to future climatic pressures and generate spatial risk assessments for climatic change scenarios. It is possible to generate preferences for other aspects of climate, e.g., Growing Degree Days, with appropriate data (Pakeman et al. 2022).

- Refine climatic (temperature and precipitation) thresholds used in this analysis by using calculated change (Rivington and Jabloun, 2022) between baseline and observed and future climatic gradients and spatial patterns.
- Map quadrat locations within the respective 10 km grid squares and use habitat and/or vegetation community maps (whichever is available) to extrapolate and generate mapping of climate preference values for the respective habitats. Habitat and community correspondence tables have been previously developed (https://hub.jncc.gov.uk/assets/9e70531b-5467-4136-88f6-3b3dd905b56d).
- Overlay with maps of monthly temperature and precipitation change for future projections (2020-2049 and 2050-2079) generated by Rivington and Jabloun (2022) to identify hotspots of habitat vulnerability and risk to shifting climatic patters. Depending on the data availability, this assessment could be done either at regional (e.g., Cairngorms National Park) or national scale.

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