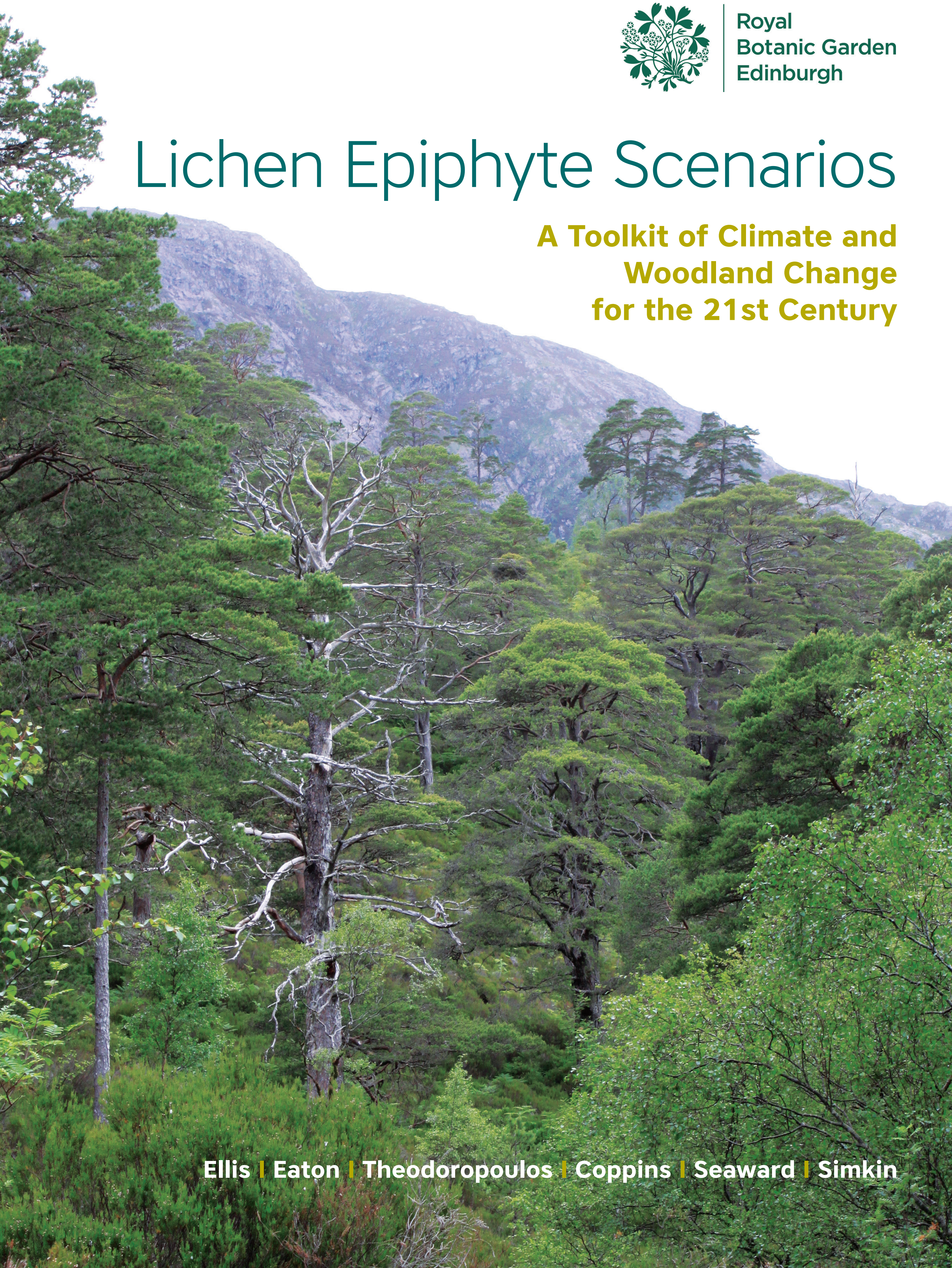
Royal Botanic Garden Edinburgh

Lichen Epiphyte Scenarios

A Toolkit of Climate and Woodland Change for the 21st Century



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Contents

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Royal Botanic Garden Edinburgh

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The British Lichen Society

climate change Scotland's centre of expertise connecting climate change research and policy

Summary

Decisions taken today can have long-term consequences; this is especially true in the management of forests and woodlands, where the lifespan of a single generation of trees, and the response of biodiversity and ecosystem function, far exceeds that of human policies and strategies.

The impact of forest/woodland management decisions can therefore span decades or centuries, and thinking about and exploring a range of future scenarios can help to identify robust decisions in the face of uncertainty.

This tool-kit of Lichen Epiphyte Scenarios provides a way to compare present-day (baseline) and future environmental suitability (2050s and 2080s) for 382 lichens that are important in forest biodiversity, allowing for:

- The long-term reduction in SO_2 pollution observed across the UK,
- The Met Office Hadley Centre's ensemble projections of future climate change, and
- Potential changes in tree species composition.

The user provides a standard 10 km grid reference for a site of interest, with an opportunity to input woodland tree species composition to compare baseline and future (2050s and 2080s) environmental suitability. Comparisons can be made for individual lichen epiphytes, or for an assemblage of species.

A shift in values of environmental suitability (positive or negative change) can be compared among epiphyte species or assemblages, to assess the degree of exposure to expected climate change and including the effect of woodland processes such as natural/managed succession, or tree disease.

It is important to consider the following key points:

- The toolkit does not forecast or 'predict' the future, but provides a means to explore alternative scenarios of climate/woodland change, and to develop plans and strategies to manage epiphytic diversity while taking future uncertainties into account.

- The toolkit is based on the British distribution of species (a subset of their total range); in assessing the species response to climate change, the toolkit will be most reliable for northern Britain (e.g. Scotland), and will become less reliable at southern sites.

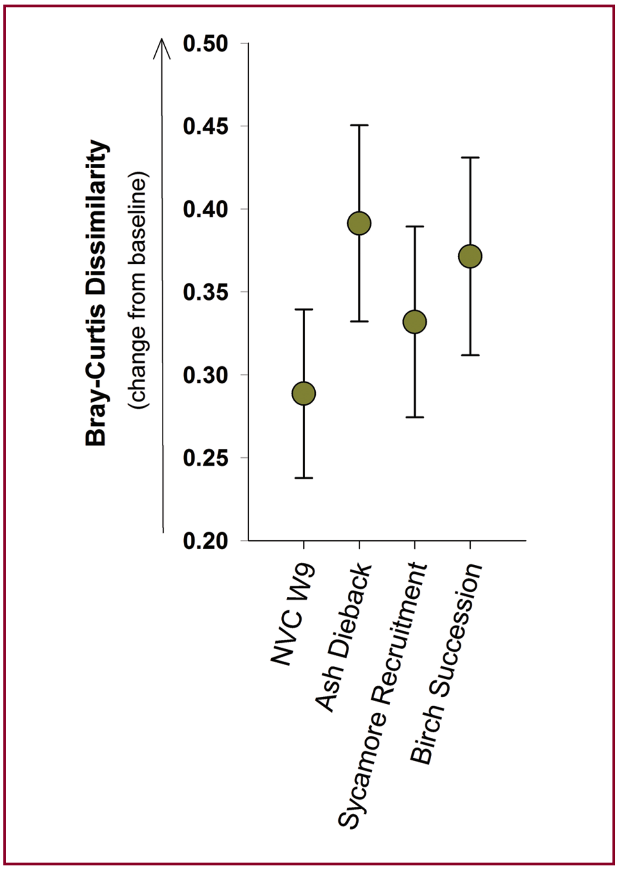
- A positive shift in environmental suitability indicates improving conditions for a species or assemblage, but it does not follow that the species is more likely to actually occur within a site. Actual occurrence depends on a range of local ecological factors also. For example, projections through to the 2080s suggested ameliorating conditions for the lichen *Bacidia incompta* (with declining summer precipitation), though the actual occurrence of this species depends not just on large scale environmental suitability or woodland composition, but also on the provision of veteran trees and their associated microhabitat. Local habitat quality remains a key factor.

- Likewise, a negative shift may evidence declining conditions, but does not suggest a species will become extinct from a site if suitable local habitat is maintained. By way of analogy, glacial relict species exist within local refugia despite unsuitable macroclimatic conditions during the Holocene. An example is the vascular plant *Dryas octopetala* which was widespread during the late-glacial period and persists in Britain in isolated patches of suitable local habitat.

- Nevertheless, increasing suitability within the toolkit points cautiously to a positive opportunity for improved species protection, while decreasing environmental suitability points to a potential risk.

A simple example of the type of analysis that is available is provided graphically (*Figure 1*), and a description follows.

Figure 1. **Points and error bars showing the relative degree of epiphyte community shift away from a present-day baseline located at '0', for a range of woodland scenarios.**



The distance of points upwards along the y-axis (vertical axis) demonstrates the mean difference in environmental suitability among 382 epiphytes, between the baseline environment at '0' (present-day), and the 2050s environment under a medium greenhouse gas emissions scenario. This is for a Special Area of Conservation qualifying ashwood (community type NVC W9) in the Scottish borders: (i) considering only larger-scale environmental (climate) change, (ii) considering larger-scale environmental (climate) change plus the loss of ash (ash die back scenario), (iii) considering replacement of ash with sycamore, or (iv) with birch.

The error bars show standard deviations derived from climate model uncertainty. A loss of ash shifts the epiphyte community further away from the baseline than climate change alone, with this mitigated by succession to sycamore, and less so by birch colonisation.

Introduction

1.1

CLIMATE CHANGE challenges society to make robust decisions that protect natural, cultural and economic assets when faced with uncertainty. This challenge is as relevant to biodiversity, including species conservation, as it is to flooding, food security or health.

Scientists are in broad agreement that human-induced greenhouse gas emissions are shifting the global climate[1]. However, there is a degree of uncertainty at regional to local scales, as to the rate, magnitude and direction of change in different climate variables such as temperature and precipitation. Scenarios are therefore used to examine climate projections for different time periods, and for different emissions pathways, e.g. in the 2050s or 2080s, under assumptions of low, medium or high greenhouse gas emissions. Additionally, regional models developed by the UK Met Office’s Hadley Centre have made it possible to explore uncertainty within these alternative scenarios, by providing for each a spread of future climate estimates referred to as an ‘ensemble’[2].

1.2

BIOCLIMATIC MODELLING is a technique used to estimate whether for a certain species, environmental conditions may become more or less suitable than in the present-day based on a comparison with future climate scenarios[3].

Bioclimatic models do not attempt to forecast the future, or predict with certainty whether a species will be present or absent at some time-point. Simply, by characterising the set of climatic conditions within which a species occurs today (the ‘bioclimatic envelope’), bioclimatic modelling cautiously assesses the extent to which the environment may become more or less favourable at a given location, or within a certain region, based on possible trajectories of greenhouse gas emissions which inform scenarios of climate change. This information on climate change *exposure* provides a useful starting point for understanding species *vulnerability* (*Figure 2*).

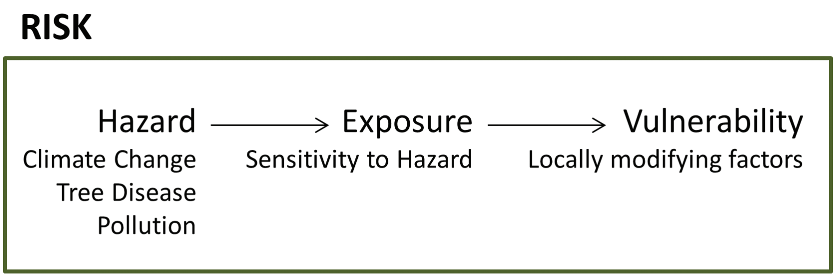


Figure 2. **Risk is perceived as having three components: hazard, exposure and vulnerability[4]. Climate change represents a hazard, with a species’ exposure measured as its sensitivity to the hazard, and its vulnerability the extent to which exposure is offset by mitigating factors. Hazards come in many forms, including the effect of tree disease, where exposure would be a species’ sensitivity to the loss of a given tree species and changed woodland composition. Changed woodland composition is incorporated alongside climate change into the Lichen Epiphyte Scenarios.**

1.3

NATURE CONSERVATION is increasingly challenged by climate change, and bioclimatic modelling can help in decision-making.

For example, priority species at sites for which the future climate is projected to become less suitable may be targets for monitoring. Remedial action to reduce additional stresses may be instigated, e.g. increasing the connectivity between and the size of local populations. For sites or regions in which (i) the climate becomes less suitable for the current assemblage of species, while (ii) becoming more suitable for species which are absent, alternative management options can be explored. These may include investment to protect the current assemblage (maintaining the *status quo*), or opting for increased connectivity to facilitate a changing species composition while retaining species richness.

1.4

REAL-WORLD DECISIONS related to nature conservation and climate change are constrained by data availability and the breadth and depth of the evidence base.

Vascular plants and animals have been the primary subjects of bioclimatic modelling to inform UK conservation[5], with model projections becoming an important component in conservation decision-making[6]. In contrast, cryptogamic plants and fungi (e.g. mosses, liverworts and lichens) – for which the UK has an international conservation responsibility – have lagged behind in terms of evidence for their exposure to climate change. This toolkit aims to redress this balance for lichen epiphytes.

1.5

LICHEN EPIPHYTES are used here as a key example, with evidence drawn from across 382 species.

Lichen epiphytes are biogeographically important in northern and western Britain including Scotland. Globally rare and internationally-important cool-temperate rainforest communities occur along the Atlantic coast, and grade into nationally-important examples of a boreal flora in the cooler and drier north-east Highlands (*Figure 3*).

Figure 3. **A diverse community of oceanic epiphytes, including *Pseudocyphellaria crocata*, which characterises the globally rare cool-temperate rainforest ecosystem along Scotland's Atlantic coast.**

Previous work has tested the application of bioclimatic models to lichens, and has validated this approach for epiphytes[7]. However, it is also well known that at a landscape-scale lichen epiphytes are sensitive not only to climate, but also to the pollution regime and woodland spatial-temporal structure[8]; this existing knowledge demands that an amalgam of environmental covariates accompany climatic variables within ecologically-plausible bioclimatic models.

1.6

LOCAL HABITAT factors such as woodland tree species composition will also affect lichen epiphyte occurrence, and these can be used to refine estimates of the larger-scale environmental suitability provided by bioclimatic models.

It is established that British tree species with contrasting bark characteristics (e.g. bark structure and/or chemistry) will host different types of epiphyte species and communities[9]. Tree species composition of a woodland stand is therefore an important additional factor in down-scaling environmental suitability. Projections for lichen epiphytes can be developed not only with respect to scenarios for larger-scale climate or pollution impacts, but taking into consideration scenarios of local change in woodland composition.

1.7

THIS REPORT provides an analysis and toolkit to explore the response of 382 lichen epiphytes, to two climate change ensembles for time-periods centred on the 2050s (medium emissions) and 2080s (high emissions). The toolkit can also accommodate shifts in woodland tree species composition, which may be evaluated by the user based on their priorities: e.g. by exploring different combinations of tree species for regenerated woodland, or for existing stands incorporating the possible effect of climate change on tree performance, or the effect of tree disease.

Section 1: **Endnotes**

[1] The 5th Assessment Report from the Intergovernmental Panel on Climate Change published in 2013 suggested that it is 'extremely likely' that human influence has been the dominant cause of increased global temperatures since the mid-20th Century (Stocker *et al.* 2013). The report and summary documents can be downloaded from: http://www.ipcc.ch/ (accessed January 2015).

[2] The UK Met Office's Hadley Centre provides 11 variants in an ensemble of spatially coherent climate projections for a given greenhouse gas emissions pathway and time-period (Sexton et al. 2010); differences among the variants demonstrate the effect of adjusting the parameters (assumptions) of a climate model and provide a spread of projected climate values which are considered to be equally likely outcomes. Additional information on the UK spatially coherent projections is available at: http://ukclimateprojections.metoffice.gov.uk/23200 (accessed January 2015). Information on the use of regional climate models is available at: http://ukclimateprojections.metoffice.gov.uk/23234 (accessed January 2015).

[3] Bioclimatic modelling has used a rich variety of statistical techniques to quantify and test the environmental niche of species from many different biological groups, and project their responses to climate change scenarios. For a recent technical review see Townsend Peterson *et al.* (2011) and for an accessible overview see Chapter 6 by Pearson (2011).

[4] The three-component model of risk was developed within the insurance industry (Crichton 1999), with the concept applied to epiphytes by Ellis (2013). The risk that is posed by exposure to large scale climate change (or other hazard) depends on local vulnerability, which includes biological processes such as gene flow (adaptation) or phenotypic plasticity, as well as manageable aspects of the environment including local habitat quality and availability of microclimatic niche space.

[5] Past examples of bioclimatic modelling which form useful background reading include the MONARCH reports on climate change risk for a range of different taxonomic groups (Harrison *et al.* 2001; Walmsley et al. 2007).

[6] Key reviews have highlighted the role of bioclimatic modelling as a component in the mixed evidence base for assessing climate change risk to biodiversity, provided by Dawson *et al.* (2011) and Thomas *et al.* (2011).

[7] Bioclimatic models were first developed for British lichens by Ellis *et al.* (2007a,b) and have been validated in numerous ways: (i) by demonstrating that independently derived post-glacial species distributions in North America occupy matching climate space to those in Britain (Braidwood & Ellis 2012), (ii) by demonstrating a functional (growth rate) sensitivity of a model epiphyte (*Lobaria pulmonaria*) to large-scale climate variability (Eaton & Ellis 2012), and (iii) by demonstrating climate signatures among epiphyte communities when comparing the Little Ice Age with 21st Century warming (Ellis *et al.* 2014).

[8] Research that has partitioned the unique effect of climate, pollution and habitat structure on epiphyte composition (Ellis & Coppins 2009) has suggested that – across mainland Britain – climate accounts for c. 6.1 % of assemblage variation, pollution c. 9.8 % and landscape habitat structure c. 6.6 %.

[9] Bark properties are an important control of epiphyte community structure (Ellis, 2012) and trees with similar bark characteristics will tend to share similar epiphyte assemblages, compared to trees with contrasting bark physical and chemical traits (as an example relevant to ash dieback, see Ellis *et al.* 2013).

Bioclimatic Methodology and Results

2.1

LICHEN SPECIES DISTRIBUTIONS were assembled from the British Lichen Society database[1], which included > 1.2 million individual records.

Records of confirmed presence were compiled across 2616 10 km grid-squares for 'corticolous' lichens which had been recorded as occurring on the bark of one or more of 15 native or naturalised British trees (see Section 3, below). These data were filtered to include only those lichen epiphyte species with a confirmed occurrence in ≥ 30 10 km grid squares. This ensured a minimum number of data points per species, for analysis. A total of 402 epiphytes met these initial criteria for bioclimatic modelling.

2.2

BASELINE ENVIRONMENTAL DATA included 12 environmental variables, compiled from three sources, and summarised at the same 10 km scale as the lichen distribution records (see Section 2.1, above).

Climate data included gridded datasets interpolated by the UK Met Office at a 5 km resolution over the period 1961-2006[2], for: (i) annual precipitation (mm), (ii) summer precipitation (mm), (iii) winter precipitation (mm), (iv) mean annual temperature (°C), and (v) mean temperature of the coldest month (°C). These variables were selected to capture a trajectory towards increased annual warmth, and potentially important shifts in precipitation seasonality, as suggested for the British climate[3]. The selected variables were also functionally relevant considering the poikilohydric nature of lichen epiphytes, with water-supply known to be a limiting factor to lichen growth, and with an interaction of the water regime with temperature[4].

Pollution data included gridded datasets interpolated by the Centre for Ecology and Hydrology[5] at a 5 km resolution over the period 2004-2006 for total deposition of: (i) acidity (keq ha^{-1} yr^{-1}), (ii) nitrogen (kg N ha^{-1} yr^{-1}), (iii) reduced nitrogen, NH_x (kg N ha^{-1} yr^{-1}), (iv) oxidised nitrogen, NO_x (kg N ha^{-1} yr^{-1}), and (v) the concentration of sulphur dioxide, SO_2 (µg.m^3). Baseline data also included the concentration of sulphur dioxide, SO_2 (µg.m^3) for the period 1987, when levels of this pollutant were higher than post-2000. This helps to account for any lag-period in the response of epiphyte species to reduced levels of this pollutant, i.e. distributions through to 2010 which reflect former SO_2 effects[6].

Woodland habitat quality at the landscape scale was included by estimating the overall extent of ancient semi-natural woodland (ha) within the UK's Ancient Woodland Inventory[7], and summed for 10 km grid-squares.

2.3

DEVELOPMENT OF BIOCLIMATIC MODELS FOR SPECIES compared their known distributions (see Section 2.1, above) to the 12 environmental variables (see Section 2.2, above) using maximum entropy modelling implemented in the program MAXENT v. 3.3.3k[8]. MAXENT was chosen based on formal tests which have demonstrated a strong statistical performance for presence-only datasets, compared to alternative techniques[9].

MAXENT projects the environmental suitability (env*S*) of grid-squares within a region, as a balance between two outcomes: (i) attempting for as uniform as possible a result, i.e. in which values of env*S* are equally likely across all grid-squares, while (ii) progressively improving predictive capacity through an adjustment of 'fit' to ensure that the mean environmental value of grid-squares in which a species is predicted to occur, is within confidence boundaries for the mean environmental value across the species' known occurrence.

The statistical fitting uses a series of functions which control the relationship of the occurrence data to environmental variables; we used an automated selection of functions.

Environmental suitability was expressed as a logistic output between 0 and 1, with a value of 0.5 corresponding to the environmental state of 'average' or 'typical' presences. Fitted models were tested using a 10-fold cross-validated area under the receiver operating characteristic curve (AUC) to assess predictive accuracy[10], by comparing model fits of environmental suitability (env*S*) with a species' known occurrence and regions without records (assumed absences).

2.4

MAXENT was used to project environmental suitability for 382 species (though including some species aggregates, as well as intra-specific taxa), representing 95% of the initial epiphyte pool of 402 epiphytes. Twenty candidate species could not be effectively modelled, and were removed from the toolkit.

Successfully modelled species had cross-validated AUC values ≥ 0.7, following a rule of thumb in which values > 0.7 and > 0.9 are considered reasonable and excellent, respectively[11]. Unsuccessfully modelled species (AUC values < 0.7) tended to be widely distributed for our baseline period, without strong biogeographic structure in Britain, such as for *Hypogymnia physodes, Lecanora chlarotera* or *Lecidella elaeochroma*.

For successfully modelled species, we estimated the relative importance of different explanatory variables in accounting for a species' response, using permutation tests[12].

2.5

SCENARIO PROJECTIONS were implemented at the same 10 km scale as the baseline (see Section 2.2), for two time-periods, and incorporating a changed pollution regime with respect to SO_2.

Scenario data for the five climate variables (see Section 2.2) were derived from the UK's HADRM3 model (implemented within UKCP09) at a spatially-coherent 25 km resolution[13]. Two climate scenarios were used[14], for the 2050s time-period under a medium emissions scenario (SRES A1B: 2050M), and for the 2080s time-period under a high emissions scenario (SRES A1FI: 2080H). For each of the two time-periods, the scenarios comprised 11 variants based on differently situated climate model parameters (i.e. a perturbed physics ensemble), with each outcome considered equally plausible.

For the future time-periods, values for pollutants and for woodland habitat quality kept their baseline values, except that projections dropped the 1987 values for sulphur dioxide, SO_2 ($\mu g.m^3$), replacing these with the lower 2004-2006 values instead. Scenarios therefore incorporate a changed climate (2050M and 2080H), as well as allowing for the potential effect of lowered SO_2 pollution on the environmental suitability (env*S*) for lichen epiphytes.

2.6

DISSEMINATION of the results of the bioclimatic modelling is through the Scenario Tool-Kit (see Section 4).

The tool-kit includes information on the environmental suitability (env*S*) of species and their changed (increased/decreased) environmental suitability (Δenv*S*), comparing baseline env*S* with scenarios of env*S* for a user-defined location (10 km grid-square). Information can be extracted for epiphyte species individually or for certain groups of lichens such as International Responsibility Species, IUCN Category Species, Priority Species, or a user-defined selection.

The values of environmental suitability (env*S*) derived from bioclimatic modelling can be adjusted to accommodate site-specific information on woodland tree species composition, providing a cross-reference to local ecological conditions (see Section 3). A summary value is calculated across multiple species in an assemblage, providing an indication of the extent to which the epiphyte community as a whole shifts in response to different scenarios. This is based on the Bray-Curtis dissimilarity metric[15], scaling between 0 (no effective change in values of env*S* between baseline and scenario), and 1 (complete change in values of env*S* between baseline and scenario). This must be used alongside the magnitude of Δenv*S* that is calculated for individual species, to compare among different scenarios.

Section 2: **Endnotes**

[1] The British Lichen Society database provides species location data for the British Isles, and represents one of the best catalogued lichen floras in the world. A status report relevant to the toolkit was provided by Simkin (2012), with up-to-date information made available through the British Lichen Society website: http://www.britishlichensociety.org.uk/recording-mapping/bls-databases (accessed January 2015).

[2] The spatial interpolation of climate data at a 5 km x 5 km scale has been developed and tested by the UK's Met Office (Perry & Hollis 2005), across c. 540 and c. 4400 temperature and precipitation stations, respectively.

[3] Observational trends tentatively support climate models in suggesting a warming British climate, alongside seasonal shifts in precipitation towards wetter winters and drier summers (Jenkins *et al.* 2007; Murphy *et al.* 2009).

[4] For a recent review of lichen physiology relevant to climatic and microclimatic factors see Green *et al.* (2010).

[5] Spatially-interpolated and gridded pollution data has been published by the Centre for Ecology and Hydrology as the NEGTAP (2001) and RoTAP (2012) reports, and is made available over the web on a site basis through the Air Pollution Information System: http://www.apis.ac.uk/ (accessed January 2015).

[6] The lichen sensitivity to SO_2 from fossil fuel combustion is well-established (Gilbert 1965; Gilbert 1970; Hill 1971), and for much of the industrial period this was the dominant pollutant controlling lichen distributions (Hawksworth & Rose 1970; Geebelen & Hoffman 2001). Levels of SO_2 have declined in the UK since the 1980s, and species ranges are recovering as a consequence (Rose & Hawksworth 1981; Hawksworth & McManus 1989; Seaward 1998), though there remains a lag-period between a decline in SO_2 and species range-filling. This lag may be explained by: (i) species dispersal limits and low recolonisation rates, and (ii) a delayed recovery of substratum chemistry, with lichen species or communities sampled from longer-lived substrata continuing to reflect past pollution regimes (Bates *et al.* 1990, 2001; Gilbert 1992).

[7] Woodlands were included from the Ancient Woodland Inventory (Roberts *et al.* 1992; Spencer & Kirby 1992) if they had continuity of tree cover since at least the mid-19th Century, and more typically ≥ 260 yr.

[8] The computer program MAXENT is widely used for species bioclimatic modelling with 'presence-only' data, and is made available as a software package by the University of Princeton: http://www.cs.princeton.edu/~schapire/maxent/ (accessed January 2015). A technical description of the implementation of maximum entropy modelling has been provided by Phillips *et al.* (2006) and Phillips & Dudík (2008), with a summary description for ecologists provided by Elith *et al.* (2011).

[9] MAXENT has shown good performance when formally tested against other statistical techniques by Elith *et al.* (2006), Hernandez *et al.* (2006) and Ortega-Huerta & Peterson (2008).

[10] The area under the receiver operating curve tests the accuracy of a diagnostic system as the rate of true and false positives (sensitivity and 1-specificity) across a range of decision-making thresholds (Swets 1988).

[11] In the interpretation of AUC values a model that is no better than random, or is perfectly diagnostic, would achieve AUC values of 0.5 or 1, respectively, with AUC > 0.7 and > 0.9 considered reasonable and excellent (Pearce & Ferrier 2000). Applied to MAXENT, an approximate AUC is generated, based on assumed absences (non-presences).

[12] MAXENT includes the opportunity to perform permutation tests on explanatory variables, in which values of a given variable are randomly permuted to measure the decrease in AUC. A large decrease in AUC (standardised to a percentage) indicates that a variable contributes importantly in explaining the observed response for that species.

[13] The UK Met Office's Hadley Centre has provided a user platform (UKCP09), which makes available spatially coherent climate projections (Sexton *et al.* 2010), at a regional scale by utilising the climate model HADRM3,

for a given greenhouse gas emissions pathway and time-period: http://ukclimateprojections.metoffice.gov.uk/22542 (accessed January 2015).

[14] Climate scenarios are based on storylines of global future social and economic pathways, and resulting greenhouse gas emissions (Nakicenovic 2000; Murphy *et al.* 2009), and are provided within bounds encompassing a scaling-up or down-scaling of emissions. The analysis here used medium and high emissions pathways for periods centred on the 2050s and 2080s, respectively.

[15] The Bray-Curtis metric (Krebs 1999) describes the difference (dissimilarity) between two communities, from 0 (identical) to 1 (completely different). Bray-Curtis is preferred to an averaged value of change across species. This can be explained in the simplified example of a two species community, if for example Sp. A transitions from an environmental suitability of 0.5→0 (= -0.5) and Sp. B from 0→0.5 (= +0.5), the average degree of change is 0, though the actual dissimilarity is 1 (complete switch in community composition). However, the interpretation of the Bray-Curtis metric should be combined with an understanding of species values in environmental suitability (env*S*), because a community of two species which transition from env*S* values of 0.01→0 and 0.05→0, and from values of 0.9→0 and 0.95→0, would both score a change of 1, though the felt consequences of the shifted env*S* may be very different.

Tree Species Composition

3.1

SELECTION OF TREE SPECIES was based on National Vegetation Classification (NVC) and other accounts of native tree species in semi-natural habitats of upland Britain, as well as incorporating 'non-native' naturalised trees which may expand under climate change[1]. The selection of tree species was limited to those with > 1000 unique lichen records for the baseline period 1961-2010 (see Section 2), making it possible to robustly assess a lichen species' association with different trees. Fifteen tree species fulfilled these criteria.

Nine tree species represented the native and dominant canopy elements in Britain's semi-natural upland woods: alder (*Alnus glutinosa*), ash (*Fraxinus excelsior*), aspen (*Populus tremula*), birch (*Betula pendula* & *B. pubescens*), elm (*Ulmus* spp.), juniper (*Juniperus communis*), oak (*Quercus petraea* & *Q. robur*), Scots pine (*Pinus sylvestris*), and willows (*Salix* spp.).

A further three selected species are important and ecologically contrasting sub-dominant elements in semi-natural woodlands: hazel (*Corylus avellana*), holly (*Ilex aquifolium*), and rowan (*Sorbus aucuparia*). We acknowledge however that hazel can be a dominant canopy element such as where it forms oceanic hazelwood.

The final three selected tree species tend to have more southerly distributed 'native ranges' in Britain/Europe though have been introduced and/or naturalised into northern and upland systems; they represent transitional elements which are expected to become more abundant as climate change progresses: beech (*Fagus sylvatica*), lime (*Tilia* spp.) and sycamore (*Acer pseudoplatanus*).

3.2

DATA AVAILABILITY, and in particular lower recording effort at a habitat-scale, made it impossible to include the full range of tree species which may increase to dominance in Scotland's woodlands under climate change (e.g. hornbeam or sweet chestnut) or certain sub-dominant species which are important in Scotland's woodlands now, or may become increasingly important in the future (e.g. whitebeam, or wild & bird cherry).

3.3

LICHEN SPECIFICITY was calculated as the proportion of records for each lichen epiphyte that was associated with each of the tree species, thereby providing an estimate of lichen preference for a given tree. The lichen specificity is used within the toolkit to modify the value of environmental suitability (env*S*) by using a simple correction that accounts for the tree species composition in a woodland stand:

$$\text{Corrected env}S = \text{env}S * [(\text{Pr}_i * \text{Tf}_i/5) + (\text{Pr}_j * \text{Tf}_j/5) \ldots]$$

Where Pr is the proportion of records for an epiphyte species associated with a given tree (*i, j,* ...), and Tf is the frequency of a given tree species (*i, j,* ...) within a woodland stand calculated on a 5-point scale that is analogous to scores used in the UK's National Vegetation Classification.

Values for trees between 1 and 5 are therefore equivalent to the upper bounds of frequency classes (or 'constancy') within the NVC. Considering a series of subplots within a stand, the occurrence of a given tree species is estimated in five classes: up to 20% of plots (1, or a proportion/weighting factor of '0.2'), 21-40% (2, or '0.4'), 41-60% (3, or '0.6'), 61-80% (4, or '0.8'), or in 81-100% of plots (5, or '1').

3.4

SCENARIOS OF CHANGES IN WOODLAND COMPOSITION can be included by adjusting the types of trees present, or their frequencies (and weighting factors), in comparing a baseline and scenario. Scenarios therefore include the option of incorporating changed climate (temperature, precipitation) and pollution regimes (range filling to accommodate lowered SO_2) in order to examine the interactive effect of larger-scale environmental change alongside shifting woodland composition.

Section 3: **Endnotes**

1 The selection of trees was representative of eight upland NVC woodland types (Rodwell 1991; Averis *et al.* 2004), W3: *Salix pentandra-Carex rostrata* woodland, W4: *Betula pubescens-Molinia caerulea* woodland, W7: *Alnus glutinosa-Fraxinus excelsior-Lysimachia nemorum* woodland, W9: *Fraxinus excelsior-Sorbus aucuparia-Mercurialis perennis* woodland, W11: *Quercus petraea-Betula pubescens-Oxalis acetosella* woodland, W17: *Quercus petraea-Betula pubescens-Dicranum majus* woodland, W18: *Pinus sylvestris-Hylocomium splendens* woodland, and W19: *Juniperus communis* ssp. *communis-Oxalis acetosella* woodland. The selection also included aspen, which has more recently been recognised for its biodiversity interest (Cosgrove & Amphlett 2002; Parrott & MacKenzie 2008), and hazel (Coppins *et al.* 2002; Coppins & Coppins 2012). The selection of trees which may expand into Scottish woodlands was based on a major review with bioclimatic analysis addressing the impacts of climate change on British woodlands (Berry *et al.* 2012): http://www.forestry.gov.uk/pdf/Woodland_BioD_Tech_Report_70312_corrected.pdf/$FILE/Woodland_BioD_Tech_Report_70312_corrected.pdf (accessed January 2015).

SECTION 4

Scenario Toolkit

http://rbg-web2.rbge.org.uk/lichen/scenarios/index.php

4.1

SITE LOCATION. Enter a site location as a standard 10 km grid-reference (i.e. letters and numbers); in the example here, Morrone Birkwood (NO19) has been selected (*Figure 4*).

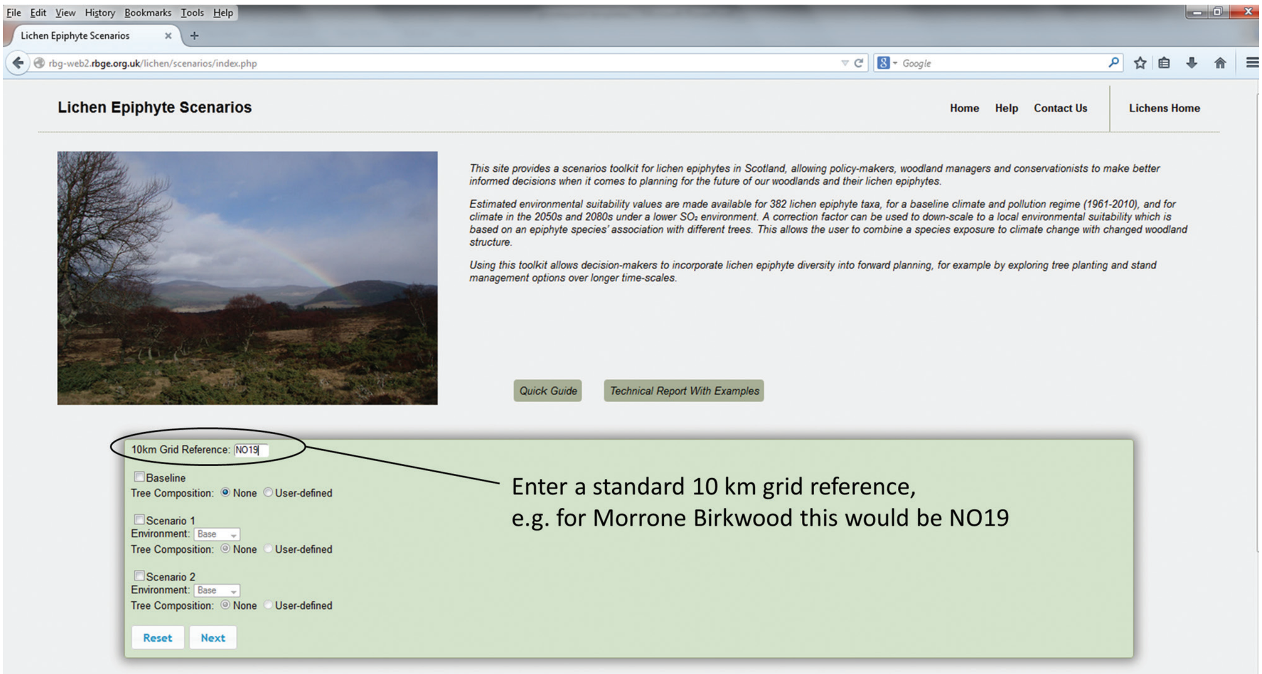


Figure 4. **The home page and input entry options for the Lichen Epiphyte Scenarios toolkit.**

4.2

BASELINE AND SCENARIO. Selecting the 'Baseline' environmental scenario (*Figure 5*) allows a comparison of lichen species environmental suitability (env*S*) determined by 'present-day' climate, pollution, and woodland landscape values, with those of future scenarios. Baseline scenarios can be modified by incorporating a user-defined tree composition.

Select up to two contrasting future scenarios to compare with the baseline. These future scenarios could be the baseline environment with a different woodland composition, or a choice of two contrasting climate change scenarios: a 2050s medium greenhouse gas emissions pathway (2050M), and a 2080s high greenhouse gas emissions pathway (2080H), each implemented with lowered SO_2 pollution.

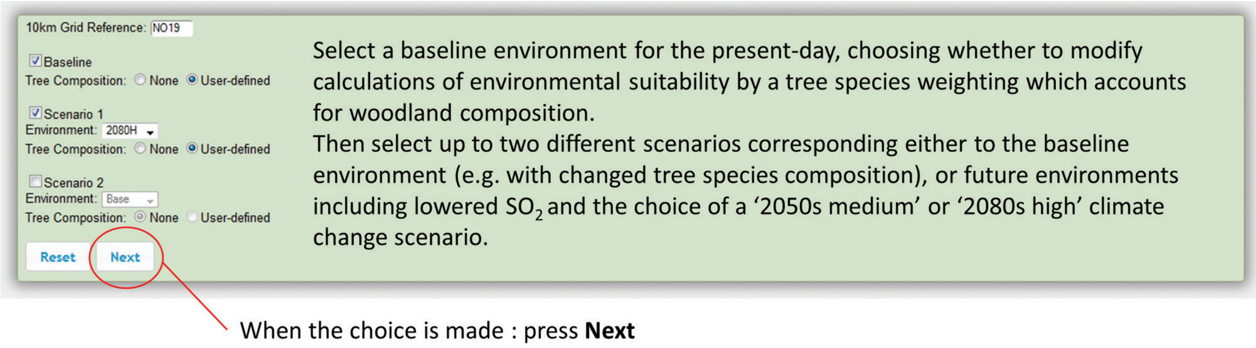


Figure 5. **Select scenario options, flexibly combining the larger scale environment (baseline, 2050M and 2080H) with modification of woodland tree species composition as required.**

In this example for Morrone Birkwood a single 2080H scenario is chosen, with the option to modify tree species composition for the baseline and 2080H. When choices are made, press 'Next'.

4.3

LICHEN SPECIES SELECTION. Scroll, or use the search and sort functions to select lichen species of interest, or 'select all' (*Figure 6*). Species nomenclature mostly follows the British Lichen Flora by Smith *et al.* (2009), with some recent exceptions, e.g. *Mycoblastus fucatus* = *Violella fucata*. If in doubt, consult the British Lichen Society Taxon Dictionary: http://www.britishlichensociety.org.uk/resources/lichen-taxon-database.

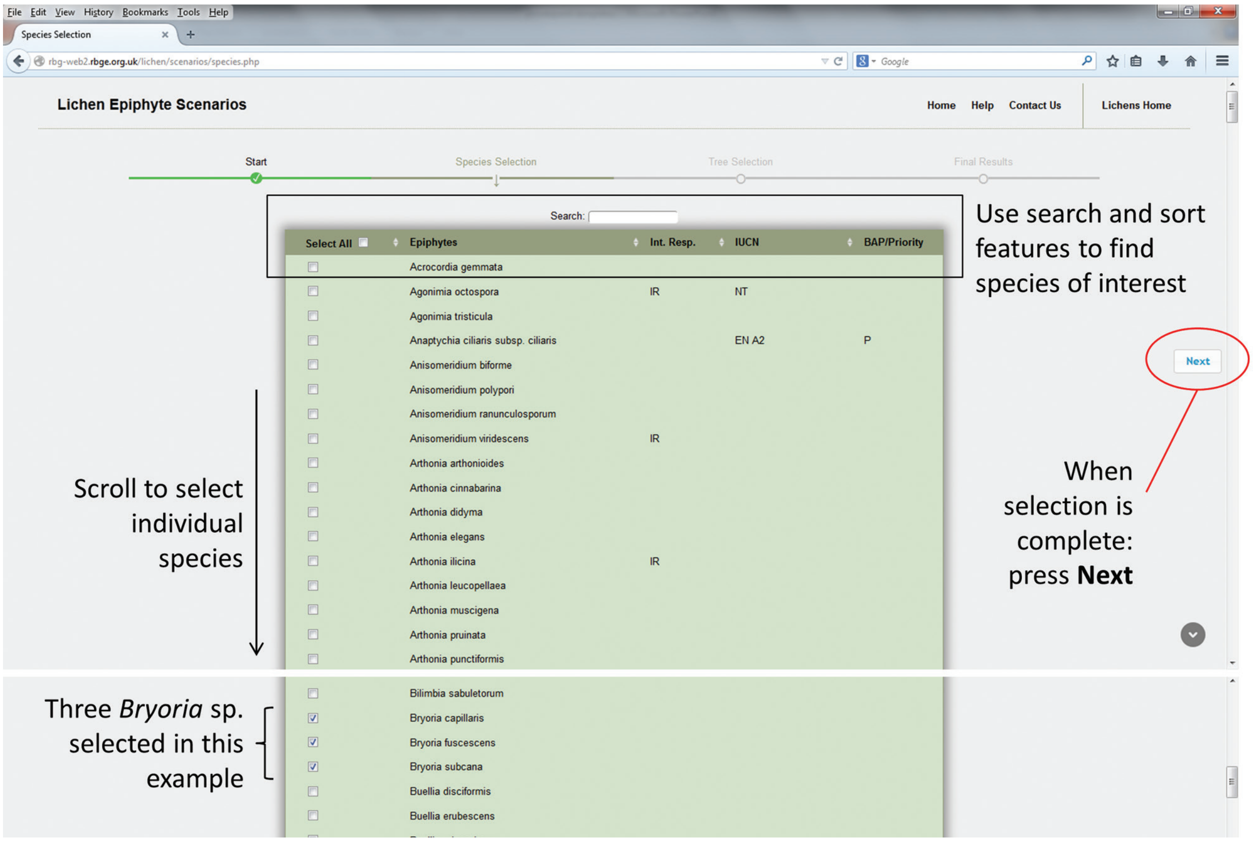


Figure 6. **Select particular lichen species or groups of interest for analysis, or select all species for a generic assessment of epiphytic environmental suitability.**

In this example for Morrone Birkwood (NO19), three *Bryoria* species have been selected; once a selection is complete, press 'Next'.

4.4

TREE SPECIES SELECTION. If chosen as an option, tree species composition for the baseline and any scenarios may now be selected (*Figure 7*).

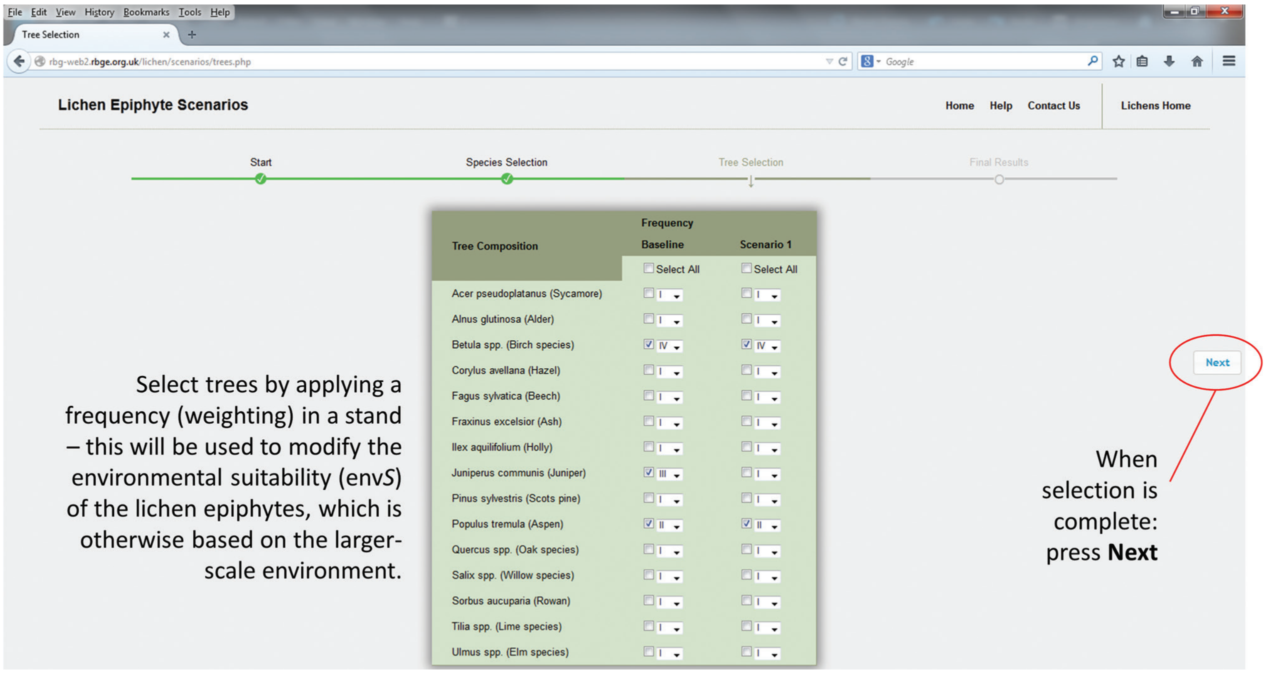


Figure 7. **Select weightings to reflect the composition of tree species in a woodland stand. This can be used to explore the consequence of hypothetical scenarios in future woodland change.**

In the example for a stand at Morrone Birkwood, the baseline selection includes a high frequency value for birch (frequency of IV, equivalent to a weighting factor of 0.8), with aspen and juniper as sub-dominants (frequencies of II and III, weighting factors of 0.4 and 0.6, respectively).

In the example scenario, juniper has been dropped from the stand in order to combine the 2080s high greenhouse gas emissions pathway (2080H) with woodland change that encapsulates dieback caused by the juniper pathogen *Phytophthora austrocedrae*.

4.5

RESULTS. The results page (*Figure 8*) can be printed out, and provides for each species:

i For the baseline, environmental suitability values (env*S*) which can be broadly interpreted as a 'likelihood' of occurrence,

ii For the scenarios, the range, mean env*S* and standard deviation where this incorporates climate model uncertainty (i.e. for 2050M and 2080H). A single env*S* value is provided where the baseline environment is also the scenario,

iii The mean difference (positive or negative change) and standard deviation of env*S*, when comparing the baseline and scenario values.

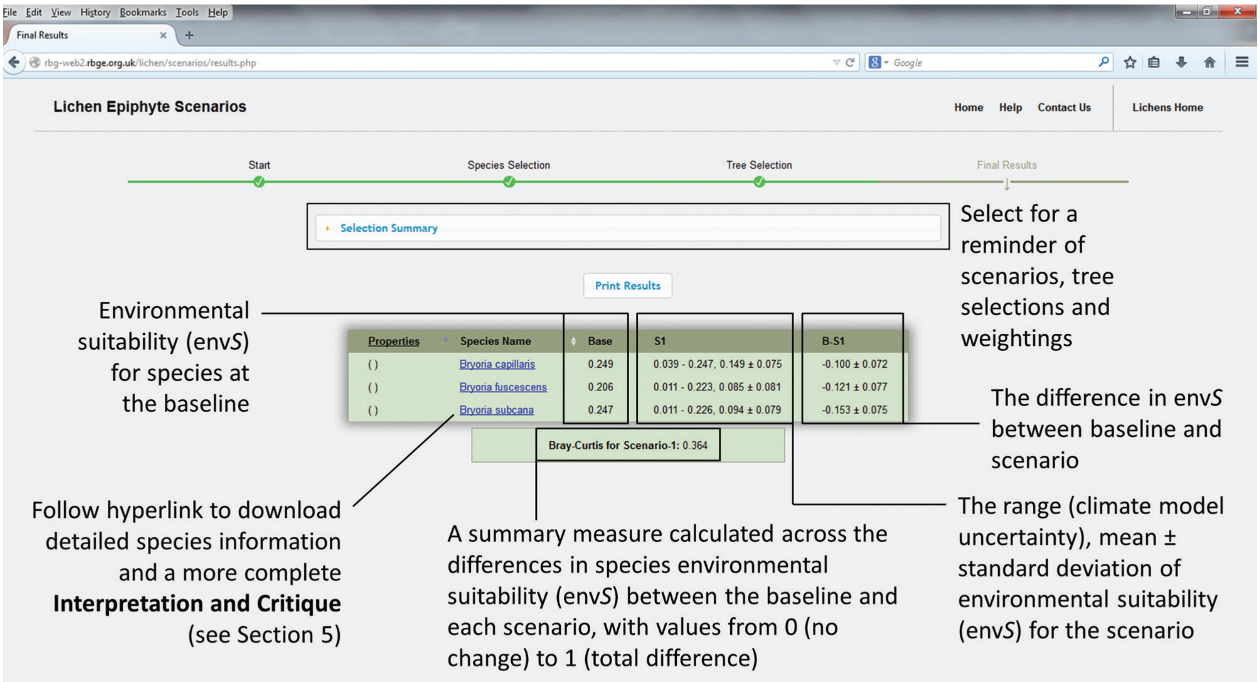


Figure 8. **The interpreted results page for the analysis based on three *Bryoria* species.**

In the case of the *Bryoria* species, the analysis here (2080H, juniper dieback) suggests an average 53% reduction in env*S*: 1- {[(0.149 + 0.085 + 0.094) / 3] / [(0.249 + 0.206 + 0.247) / 3)]}

A measure of community level change (env*S* sampled across all species) uses the Bray-Curtis metric to calculate dissimilarity values between 0 (no change) and 1 (complete change).

4.6

EXAMPLE QUESTION 1.

The Relative Importance of Climate Change and/or Tree Disease (Ash Dieback) on a Site Basis

A site location (NH52) is entered for Urquhart Bay (*Figure 9*) which contains Annex 1 habitat of 'Alluvial forest with *Alnus glutinosa* and *Fraxinus excelsior*' and is designated as a European Special Area of Conservation.

Figure 9. **Input of site and combined baseline and scenarios for Urquhart Bay.**

Baseline and two scenarios are used (each with a 2050 medium emissions pathway), and with an option to modify tree species composition. All lichen species are selected for a generic evaluation of climate and tree disease (ash dieback) impacts on epiphytes (*Figure 10*).

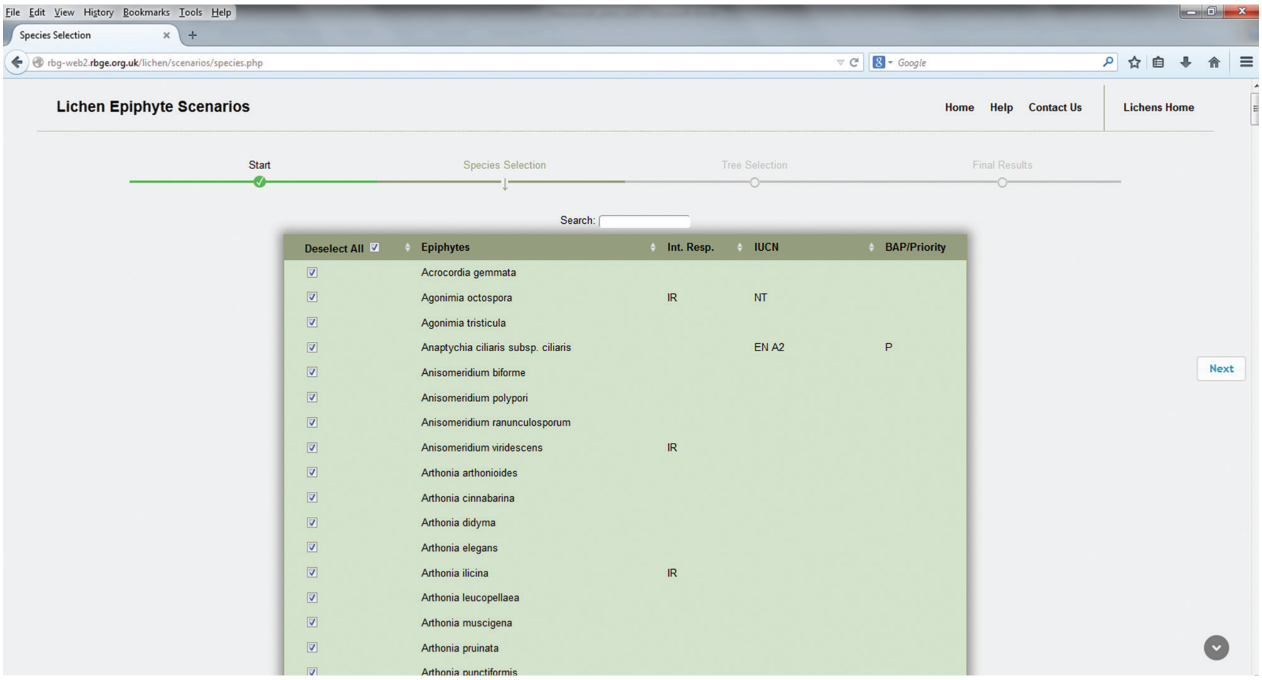


Figure 10. **Use the 'Select All' function to perform a generic analysis for the impact of the scenarios on epiphytes.**

Tree frequency scores are entered for a woodland stand (*Figure 11*). As an example:

- Baseline = the frequencies of dominant species within the site's NVC community W7: *Alnus glutinosa-Fraxinus excelsior-Lysimachia nemorum* woodland.
- Scenario 1 (2050M) = woodland composition remains the same, though with a changed climate through to the 2050s (and lowered SO_2 pollution environment).
- Scenario 2 (2050M) = woodland composition altered by a loss of ash in an ash dieback scenario, also with a changed climate through to the 2050s (and lowered SO_2 pollution environment).

Tree Composition	Frequency Baseline	Scenario 1	Scenario 2
	☐ Select All	☐ Select All	☐ Select All
Acer pseudoplatanus (Sycamore)	☐ I	☐ I	☐ I
Alnus glutinosa (Alder)	☑ IV	☑ IV	☑ IV
Betula spp. (Birch species)	☑ II	☑ II	☑ II
Corylus avellana (Hazel)	☐ I	☐ I	☐ I
Fagus sylvatica (Beech)	☐ I	☐ I	☐ I
Fraxinus excelsior (Ash)	☑ III	☑ III	☐ I
Ilex aquilifolium (Holly)	☐ I	☐ I	☐ I
Juniperus communis (Juniper)	☐ I	☐ I	☐ I
Pinus sylvestris (Scots pine)	☐ I	☐ I	☐ I
Populus tremula (Aspen)	☐ I	☐ I	☐ I
Quercus spp. (Oak species)	☑ I	☑ I	☑ I
Salix spp. (Willow species)	☑ I	☑ I	☑ I
Sorbus aucuparia (Rowan)	☐ I	☐ I	☐ I
Tilia spp. (Lime species)	☐ I	☐ I	☐ I
Ulmus spp. (Elm species)	☐ I	☐ I	☐ I

Figure 11. **The selection of tree species maintaining the same composition for the baseline and a 2050M scenario (S1), and losing ash for a 2050M scenario (S2).**

The summary Bray-Curtis statistic (*Figure 12*) shows that the degree of changed environmental suitability (env*S*) when ash dieback is considered a possibility is much higher (0.409), than for the 2050M climate change scenario alone (0.183). What are the consequences for individual species?

Inspection of the column B-S2, which measures the difference in environmental suitability between the baseline and Scenario 2 (ash dieback scenario), demonstrates that across species this change is mostly negative.

Properties	Species Name	Base	S1	B-S1	S2	B-S2
( )	Acrocordia gemmata	0.191	0.098 - 0.218, 0.195 ± 0.033	0.004 ± 0.032	0.015 - 0.034, 0.030 ± 0.005	-0.161 ± 0.005
(IR NT)	Agonimia octospora	0.009	0.024 - 0.121, 0.064 ± 0.031	0.056 ± 0.030	0.021 - 0.106, 0.056 ± 0.027	0.047 ± 0.026
( )	Agonimia tristicula	0.171	0.112 - 0.186, 0.149 ± 0.025	-0.022 ± 0.023	0.020 - 0.034, 0.027 ± 0.005	-0.144 ± 0.004
(EN A2 P)	Anaptychia ciliaris subsp. ciliaris	0.019	0.008 - 0.140, 0.049 ± 0.046	0.030 ± 0.044	0.001 - 0.013, 0.005 ± 0.004	-0.015 ± 0.004
( )	Anisomeridium biforme	0.151	0.060 - 0.144, 0.121 ± 0.024	-0.031 ± 0.023	0.020 - 0.047, 0.040 ± 0.008	-0.112 ± 0.007
( )	Anisomeridium polypori	0.170	0.153 - 0.190, 0.180 ± 0.012	0.009 ± 0.011	0.038 - 0.047, 0.045 ± 0.003	-0.126 ± 0.003
( )	Violella fucata	0.172	0.034 - 0.149, 0.107 ± 0.040	-0.065 ± 0.038	0.029 - 0.130, 0.093 ± 0.035	-0.079 ± 0.033
(IR NT P)	Wadeana dendrographa	0.049	0.111 - 0.384, 0.256 ± 0.099	0.207 ± 0.094	0.006 - 0.021, 0.014 ± 0.005	-0.036 ± 0.005
( )	Xanthoria candelaria sensu lato	0.063	0.011 - 0.070, 0.049 ± 0.021	-0.014 ± 0.020	0.004 - 0.027, 0.019 ± 0.008	-0.044 ± 0.008
( )	Xanthoria ucrainica	0.067	0.021 - 0.097, 0.058 ± 0.028	-0.009 ± 0.027	0.008 - 0.036, 0.021 ± 0.010	-0.046 ± 0.010

Bray-Curtis for Scenario-1: 0.183
Bray-Curtis for Scenario-2: 0.408

Figure 12. **The results table for the example of an ash dieback impact at Urquhart Bay through to the 2050s.**

4.7

EXAMPLE QUESTION 2.

Resilience Options for Ash Dieback

Keeping with the example of Urquhart Bay Annex 1 habitat ('Alluvial forest with *Alnus glutinosa* and *Fraxinus excelsior*), – and having highlighted the risk posed by ash dieback (see Section 4.6, Example Question 1), it may be interesting to explore alternative pathways of forest management following a loss of ash.

Site location (NH52) is therefore entered for the Baseline (cf. *Figure 9*), with two scenarios (each with a 2050 medium emissions pathway), and with an option to modify tree species composition. As with Example Question 1, select all lichen species for a generic evaluation of climate and ash dieback impacts on epiphytes (cf. *Figure 10*).

Tree frequency scores are entered for the woodland stand (*Figure 13*):

- Baseline = the frequencies of dominant species within the site's NVC community W7: *Alnus glutinosa-Fraxinus excelsior-Lysimachia nemorum* woodland.

- Scenario 1 (2050M) = woodland composition assuming the replacement of ash with a small increase in oak and sycamore.

- Scenario 2 (2050M) = woodland composition assuming the replacement of ash with birch.

Tree Composition	Frequency Baseline	Scenario 1	Scenario 2
	☐ Select All	☐ Select All	☐ Select All
Acer pseudoplatanus (Sycamore)	☐ I	☑ I	☐ I
Alnus glutinosa (Alder)	☑ IV	☑ IV	☑ IV
Betula spp. (Birch species)	☑ II	☑ II	☑ V
Corylus avellana (Hazel)	☐ I	☐ I	☐ I
Fagus sylvatica (Beech)	☐ I	☐ I	☐ I
Fraxinus excelsior (Ash)	☑ III	☐ I	☐ I
Ilex aquilifolium (Holly)	☐ I	☐ I	☐ I
Juniperus communis (Juniper)	☐ I	☐ I	☐ I
Pinus sylvestris (Scots pine)	☐ I	☐ I	☐ I
Populus tremula (Aspen)	☐ I	☐ I	☐ I
Quercus spp. (Oak species)	☑ I	☑ III	☑ I
Salix spp. (Willow species)	☑ I	☑ I	☑ I
Sorbus aucuparia (Rowan)	☐ I	☐ I	☐ I
Tilia spp. (Lime species)	☐ I	☐ I	☐ I
Ulmus spp. (Elm species)	☐ I	☐ I	☐ I

Figure 13. **The selection of tree species to maintain composition at the baseline consistent with NVC W7 (*Alnus glutinosa-Fraxinus excelsior-Lysimachia nemorum* woodland) and for two 2050M scenarios with a loss of ash, but including either the transition to a mixture of oak and sycamore (S1), or to birch (S2). Note that sycamore is not selected into the baseline or S2, and is selected at low abundance for S1.**

The summary Bray-Curtis statistic (*Figure 14*) shows that the degree of change in environmental suitability (env*S*) is expected to be lower with the replacement of ash by oak (0.299), than replacement by birch (0.338). Inspection of the columns B-S1 and B-S2 shows the effect of different scenarios for the individual species.

Properties	Species Name	Base	S1	B-S1	S2	B-S2
( )	Acrocordia gemmata	0.034	0.029 - 0.123, 0.092 ± 0.034	0.058 ± 0.032	0.009 - 0.037, 0.028 ± 0.010	-0.006 ± 0.010
(IR NT)	Agonimia octospora	0.002	0.034 - 0.215, 0.103 ± 0.059	0.101 ± 0.056	0.011 - 0.072, 0.034 ± 0.020	0.032 ± 0.019
( )	Agonimia tristicula	0.069	0.028 - 0.079, 0.054 ± 0.018	-0.016 ± 0.017	0.012 - 0.033, 0.022 ± 0.007	-0.047 ± 0.007
(EN A2 P)	Anaptychia ciliaris subsp. ciliaris	0.017	0.002 - 0.077, 0.023 ± 0.025	0.007 ± 0.024	0.000 - 0.017, 0.005 ± 0.005	-0.012 ± 0.005
( )	Anisomeridium biforme	0.052	0.077 - 0.151, 0.119 ± 0.024	0.067 ± 0.023	0.025 - 0.050, 0.039 ± 0.008	-0.013 ± 0.008
( )	Anisomeridium polypori	0.101	0.113 - 0.151, 0.143 ± 0.011	0.042 ± 0.011	0.039 - 0.052, 0.049 ± 0.004	-0.052 ± 0.004
( )	Violella fucata	0.197	0.178 - 0.200, 0.193 ± 0.007	-0.004 ± 0.007	0.273 - 0.307, 0.296 ± 0.011	0.099 ± 0.011
(IR NT P)	Wadeana dendrographa	0.002	0.003 - 0.034, 0.015 ± 0.012	0.013 ± 0.011	0.001 - 0.011, 0.005 ± 0.004	0.003 ± 0.004
( )	Xanthoria candelaria sensu lato	0.048	0.050 - 0.067, 0.060 ± 0.006	0.012 ± 0.006	0.018 - 0.024, 0.022 ± 0.002	-0.026 ± 0.002
( )	Xanthoria ucrainica	0.068	0.078 - 0.165, 0.136 ± 0.025	0.068 ± 0.024	0.029 - 0.062, 0.051 ± 0.009	-0.017 ± 0.009

Bray-Curtis for Scenario-1: 0.298
Bray-Curtis for Scenario-2: 0.321

Figure 14. **The results table for the example of an ash dieback impact at Urquhart Bay through to the 2050s; the increase in oak and sycamore appears to be better in maintaining baseline conditions (allowing for climate change), than the succession to birch.**

Use the 'Properties' column to identify individual effects for species of conservation significance.

Bioclimatic Interpretation and Critique

5.1

SPECIES REPORTS. For each of 382 lichen taxa that were successfully modelled, additional bioclimatic details are provided as individual 'species reports'. By following a link on the Results Page (see Section 4.5), a species report can be downloaded as two separate files, and this allows the user to investigate in more detail and critique the results of the bioclimatic modelling. Details are explained below for *Bryoria subcana* (*Figure 15*).

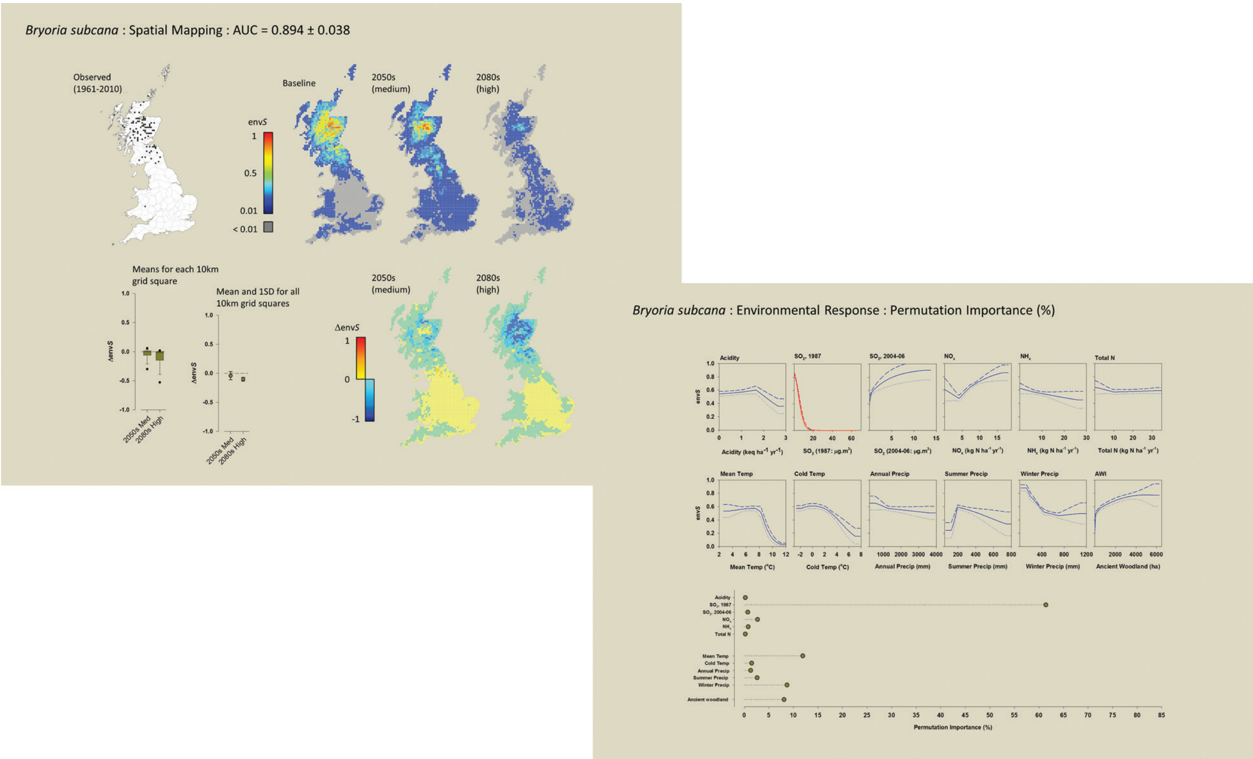


Figure 15. **Overview of the two page summary files providing further details of the bioclimatic modelling results for *Bryoria subcana*.**

5.2

SPECIES BASELINE OBSERVED DISTRIBUTION. The spatial mapping includes a plot of the baseline distribution used to build the bioclimatic models (*Figure 16*). It is important to consider that this is not all of the records for a species, but the geolocated records (1961-2010) that are associated with one or more of the 15 native and semi-natural tree species. The reliability of the bioclimatic modelling depends on the extent to which the distribution records are representative of the species' actual range as an epiphyte.

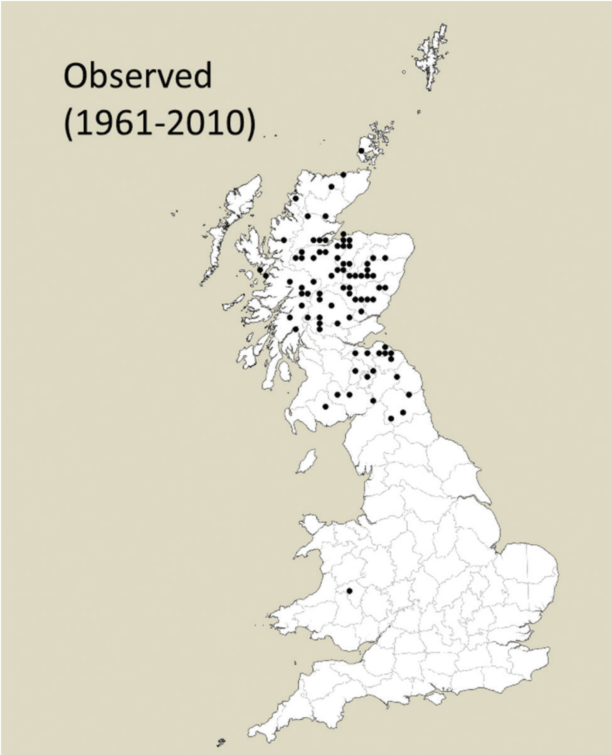


Figure 16. **The distributional data on which bioclimatic modelling was based.**

5.3

SPECIES MODELLED ENVIRONMENTAL SUITABILITY (env*S*). The following three maps (*Figure 17*) show the modelled values of environmental suitability (env*S*) for the present-day (baseline), and mean env*S* values calculated among climate model variants in the 2050M and 2080H scenarios under a lower SO_2 environment.

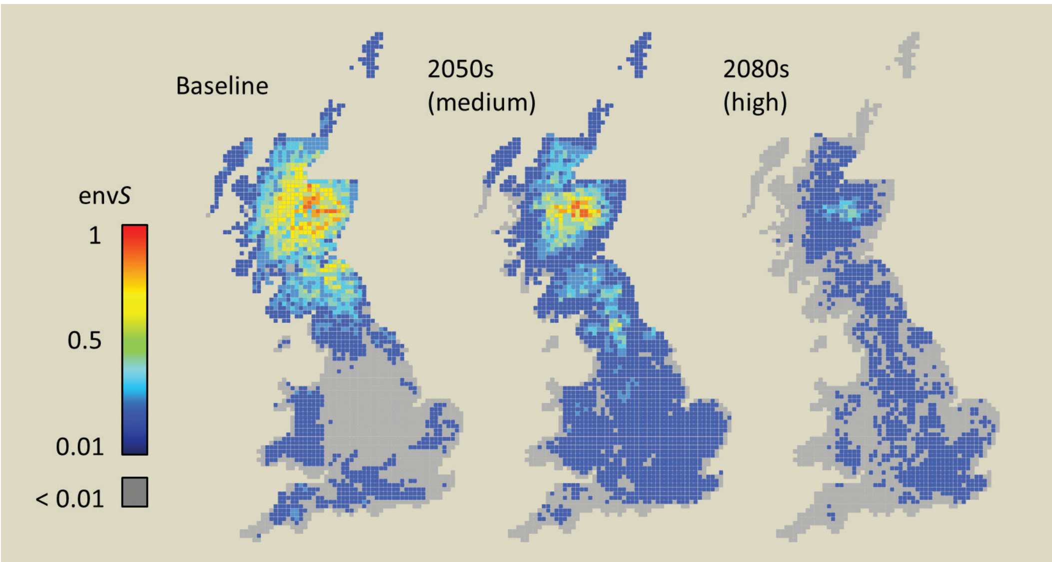


Figure 17. **Maps to show spatial trends in environmental suitability for the baseline and under the 2050s medium emissions and 2080s high greenhouse gas emissions scenarios.**

Concerning pollution, the interpretation of the scenario values of env*S* may be appropriate across Britain; for example, the env*S* of *Bryoria subcana* is seen to increase in central England presumably as a consequence of an observed and progressive decline in SO_2 pollution. However, the interpretation of scenario values in env*S* related to climatic effects is likely to be accurate for northern Britain (e.g. Scotland), but increasingly unreliable for central and southern Britain. This is because the observational data under-pinning the bioclimatic modelling were for Britain only, and do not therefore capture the full environmental tolerance of a species where it occurs outside Britain in warmer/drier climates.

5.4

SPECIES CHANGE IN ENVIRONMENTAL SUITABILITY (ΔenvS). Two further maps (*Figure 18*) show the difference in environmental suitability (Δenv*S*) between the baseline and the 2050s medium emissions and 2080s high emissions scenarios. They aid interpretation in spatial patterns of increasing/decreasing env*S*. In the example for *Bryoria subcana*, the increase in env*S* for central England is potentially offset by a long-term decline in climatic suitability within the core area of its range in northern Britain and especially north-eastern Scotland.

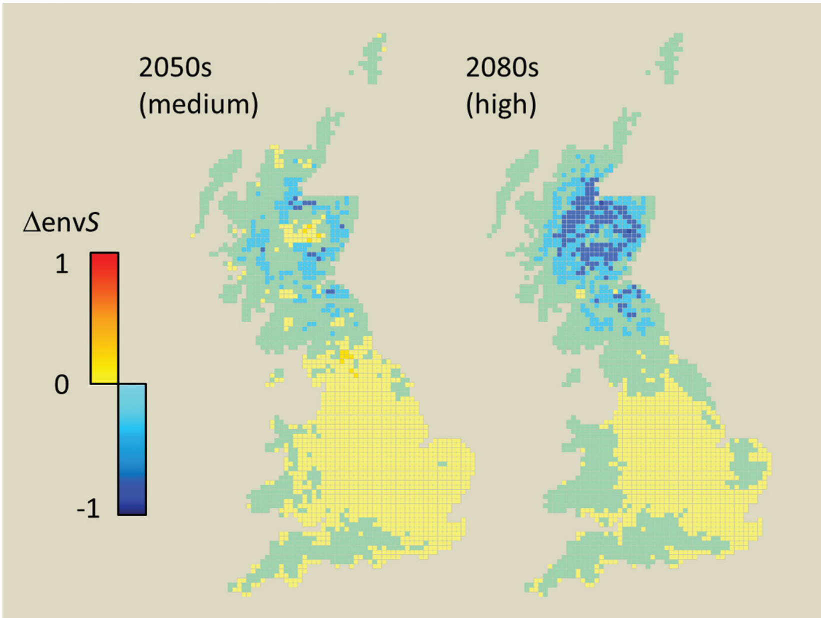
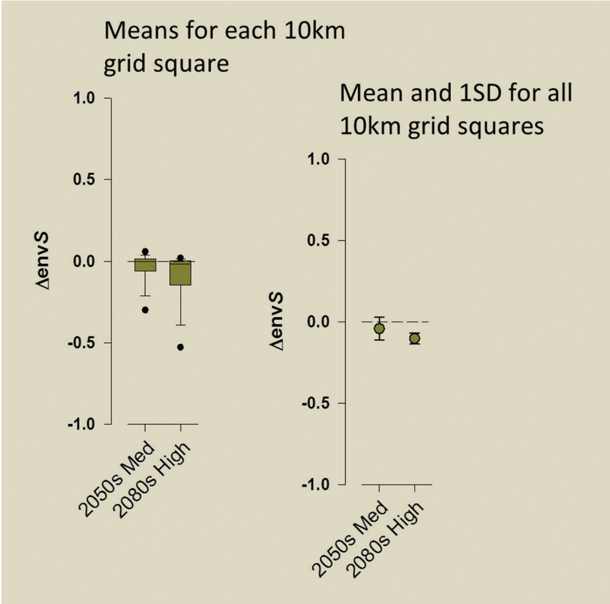


Figure 18. **Values of Δenv*S* showing the direction of travel in environmental suitability, either increasing or decreasing based on the spatial comparison of baseline and scenarios.**

5.5

VARIABILITY IN CLIMATE MODELS. The two graphs at the lower left demonstrate the variability in a species' environmental suitability (env*S*), both the spatial variability and that related to uncertainty in the Met Office Hadley Centre's climate models (*Figure 19*).

Figure 19. **Variability in the species bioclimatic response, with box plots showing variation in the mean ∆env*S* sampled across all grid squares, and point-plots showing the averaged mean ∆env*S* across all grid squares, with the variation attributable to climate model uncertainty.**



The first box-plot shows the degree of variation in changed environmental suitability (mean ∆env*S*) across each of the 2616 10km grid-squares (including the median, interquartile range, 10th and 90th percentiles (whiskers), and 5th and 95th percentiles (circles)).

The second point-plot shows the average across all 10 km grid-squares of the mean ∆env*S* and its standard deviation, providing an estimate for each species of overall variability contained within an ensemble of climate scenarios.

5.6

SPECIES RESPONSES. To allow an assessment in the validity of the bioclimatic modelling – for example, as more autecological data become available – species response curves (*Figure 20*) are provided for each of the 12 environmental variables; with env*S* on the y- or vertical-axis.

Note that if two or more variables are correlated, and one of these variables was selected as an important explanation for the species response, then the response to the co-variables may appear negligible. The most important variable in the model (highest permutation importance) is highlighted in red. Response curves can be combined with standard UK projections of future climate change to better understand a species' projected response: see http://ukclimateprojections.metoffice.gov.uk/21708.

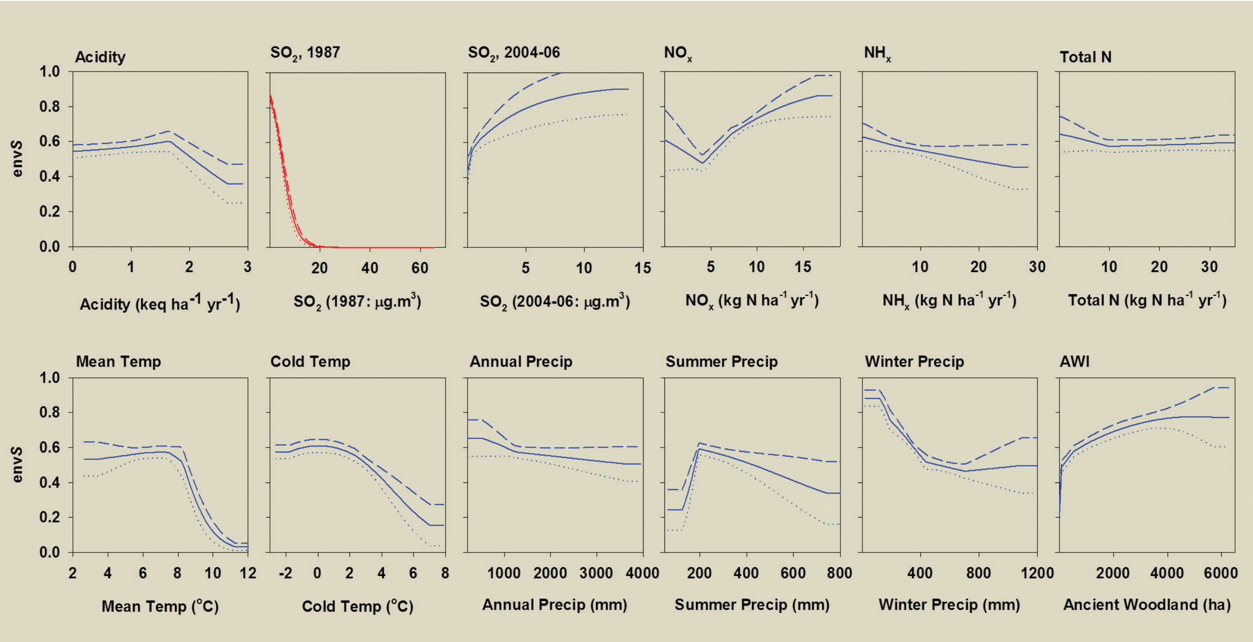


Figure 20. **Plots for the species modelled response to each of the explanatory bioclimatic variables.**

5.7

PERMUTATION IMPORTANCE. Permutation tests were performed on explanatory variables; a high permutation importance (%) indicates a greater dependency of the species' modelled response on that variable (*Figure 21*). However, other variables can play an important role, e.g. the loss of suitable environmental space for *Bryoria subcana* in north-eastern Scotland appears to be related to its sensitivity to warming temperatures, even though SO_2 has the dominant role in explaining the species' baseline distribution.

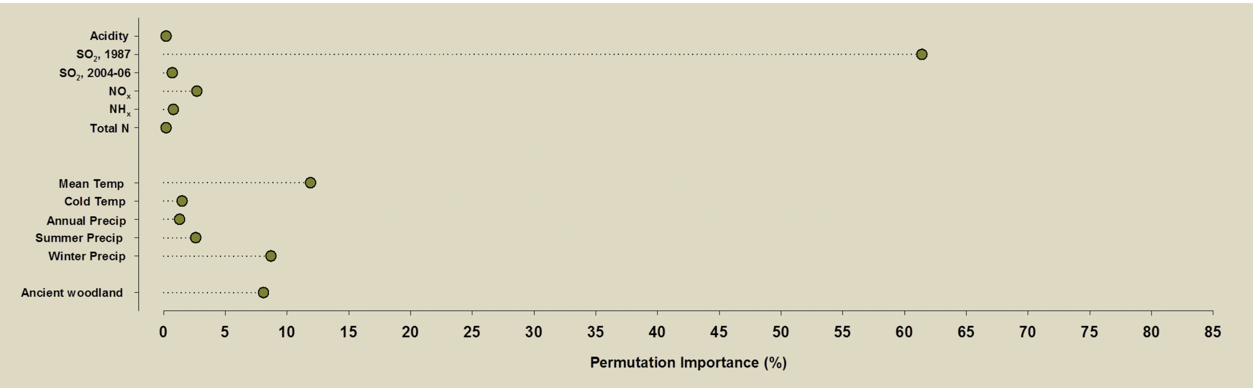


Figure 21. **Measurement of the importance of the different bioclimatic variables in explaining the modelled distribution of the species.**

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