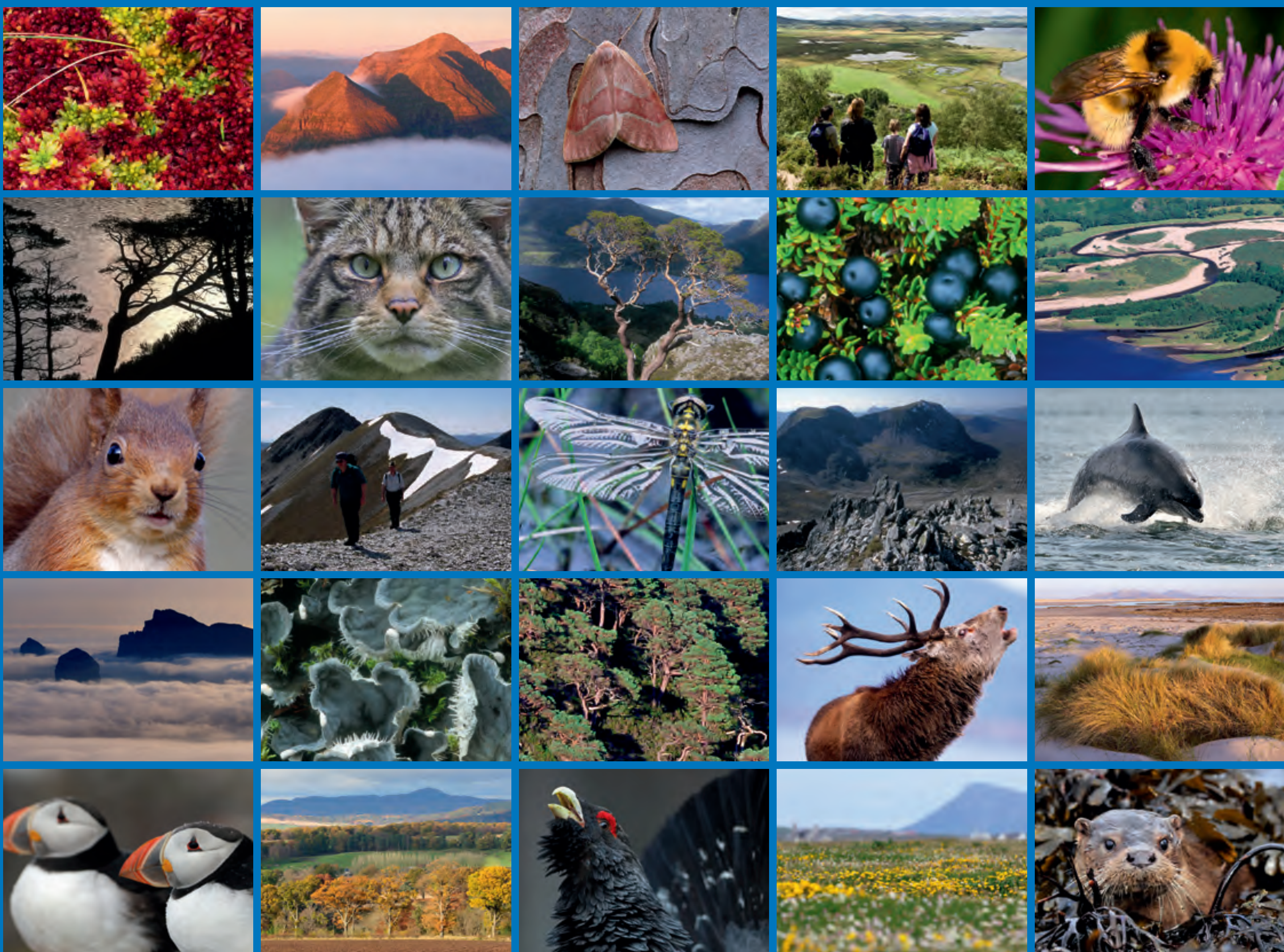
Scottish Natural Heritage
Commissioned Report No. 895

Woodland composition, climate change and the long-term resilience of lichen epiphytes at Glasdrum NNR



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C O M M I S S I O N E D R E P O R T

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Woodland composition, climate change and the long-term resilience of lichen epiphytes at Glasdrum NNR

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COMMISSIONED REPORT

Summary

Woodland composition, climate change and the long-term resilience of lichen epiphytes at Glasdrum NNR

Commissioned Report No. 895
Contractor: Royal Botanic Garden Edinburgh
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Keywords

Climate change; epiphyte; lichen; scenario analysis; tree disease.

Background

Management to protect biodiversity for individual conservation sites, e.g. SSSIs, benefits from long-term planning. Whilst it is impossible to forecast the future with absolute certainty, local actions can be designed to protect biodiversity in the long-term by using scenario analysis. This approach tests a range of current management options against a spread of potential future scenarios.

This report presents a case-study assessing the likely impact of different change scenarios on Glasdrum NNR, focusing on the status of lichen epiphytes, a group of key conservation concern for the site. Dendrochronology is used to examine the current woodland structure in terms of tree species and age cohorts. This is used to inform a 'non-intervention' scenario based on the composition of existing regeneration (declining oak), compared to active scenarios which seek to maintain or increase epiphytic diversity into the future (promotion of oak regeneration) as well as exploring the potential consequences of ash dieback.

Because forest management actions implemented during the NNR's management timeframe (2013-2023) will impact lichen epiphytes in the long-term (during the 21st Century), decisions relating to woodland structure are tested alongside projections of climate change, utilising the latest UKCP09 scenarios that account for future climate uncertainty.

The scenarios used here do not account for all aspects of future uncertainty, so are only to be used to explore potential outcomes rather than as a definitive predictive tool. Management decisions should also include contingency planning to provide resilience against additional future uncertainties.

Main findings

- Dendrochronology confirms that the woodland structure at Glasdrum has substantially changed during the last two centuries, with an older cohort of mature oak and ash trees (19th Century) that contrast with 20th Century regeneration of alder and birch.
- Scenario analysis suggests that active promotion of oak regeneration would be broadly beneficial to Glasdrum's priority epiphyte species, and would have the additional benefit of creating resilience in the lichen flora against ash dieback.

- However, the analysis also suggests that there will be winners and losers at the site; some species show a decline related to (i) climate change (across the range of future climate estimates) and (ii) a transition from alder and birch dominance at present, to oak and ash; nevertheless, most priority species of lichen would benefit from the transition to mature oak-ash woodland.
- The value of scenario analysis is highlighted in the context of a move towards a contingency planning approach to woodland management that explicitly considers future uncertainty.

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Acknowledgements

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1. INTRODUCTION

Management of Sites of Special Scientific Interest (SSSI) seeks to attain favourable condition (conservation status). However, this site-based management takes place against a background of larger-scale environmental change, such as global climate change, over which site managers have no direct control. It follows that site management plans will be most effective in the long-term if they can incorporate an understanding of larger-scale processes that can affect their success or failure. Future uncertainty makes addressing long-term and larger-scale effects, such as for global climate change, a key challenge; it is not possible to accurately forecast the climate for a given time and place. However, scenario analysis (Peterson *et al.*, 2003) can be used to maximise the chance that current management decisions are robust across the possible effects of future environmental change.

This report presents a case-study using scenario analysis to inform the consideration of management at SNH's Glasdrum National Nature Reserve (NNR) (in western Scotland), against a background of large-scale and long-term environmental change. This scenarios approach represents a step-change in conservation from prescriptive site management, that was important during the establishment phase of the SSSI network, to a dynamic and long-term approach that seeks to be robust to uncertainty, such as the risks posed by climate change and tree disease, and compatible with the large-scale 'ecosystem approach'.

1.1 The Study System

Glasdrum NNR (Figure 1) was selected for this study because (i) the site is an excellent example of Scotland's internationally important temperate rainforest, characterised by a diverse assemblage of oceanic lichens and bryophytes, and (ii) SNH is the site owner, and therefore has direct management control, which includes the potential for innovation coupled with the opportunity for long-term planning.

Nested within the Glen Creran SSSI (*c*. 714 ha), Glasdrum forms an area of 169 ha of native oak and ash wood for which SNH has developed a 10-yr management plan for the period 2013-2023 (Scottish Natural Heritage, 2014). This has the aim of securing by 2030 '*a dynamic oak and ash woodland where natural changes in the habitat are allowed to progress as far as possible while allowing us to maintain the NNR's rarest species*'. The biodiversity focus includes oceanic epiphytic lichens, which are the subject of this study. In securing a long-term future for its biodiversity, including epiphytes, SNH has stated that the vision for Glasdrum NNR includes its role as a '*key site for demonstrating adaptive management techniques where we have played our part in helping nature cope with change*'. This report explores the long-term implication of three such changes:

1. It uses dendrochronology, in a preliminary analysis, to match species composition with the age structure of trees in Glasdrum NNR (Mulcahy, 2014). This helps interpret the recent history of the site, as well as providing information on the expected future composition of the woodland, in order to scope options about how woodland succession might be managed;

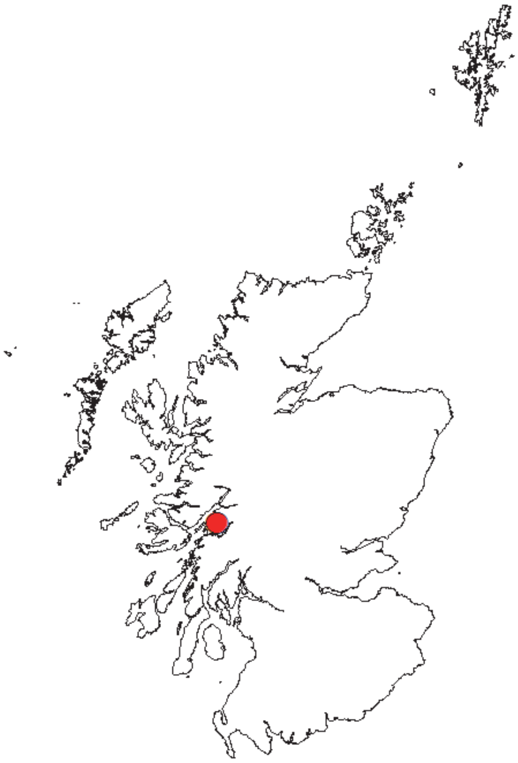

Figure 1. The location of Glasdrum on Scotland's oceanic west coast.

2. It examines the possible effect of a tree disease event, using ash dieback as an example. Recent analysis using British Lichen Society data (Worrell, 2013) has shown that ash dieback has the highest potential impact on biodiversity in oceanic western Scotland, where rare and threatened oceanic epiphytes are often associated with veteran ash trees;

3. It considers climate change alongside the transitions in tree species composition, covered in points 1 and 2. Because of the longevity of individual trees, the consequences of decisions taken through to 2030 in terms of woodland composition will be realised over the longer-term (through to the later 21st Century and beyond) in their impact on priority lichen epiphytes. Tactical decisions must therefore be future-proofed, as far as is possible, by considering the concomitant effect of climate change.

1.2 The Scenarios Approach

The study utilises an on-line toolkit developed by the Royal Botanic Garden Edinburgh with funding from the Esmée Fairbairn Foundation: the Lichen Epiphyte Scenarios toolkit (Ellis, *et al*., 2015a). The toolkit allows the user to estimate trends in lichen epiphytes' environmental suitability at a given site (ranging from unsuitable = 0, to highly suitable environments = 1), including the climate setting in three time-slices (baseline, 2050 or 2080 periods), and accounting for woodland tree species composition. The environmental suitability values for different combinations of time-slices and woodland composition can be used to explore change over time.

The Lichen Epiphyte Scenarios toolkit is targeted to the conservation of lichen biodiversity, but aims to be generally useful by showing how it is possible to engage with future uncertainty to inform management decisions. Glasdrum NNR has a broader range of objectives than the maintenance of the epiphytic lichen community, however this report uses lichens as a case-study in order to demonstrate the potential for long-term scenario analysis. This contrasts 'non-intervention', versus selected 'intervention' scenarios, each of which is compared to the baseline (Scenario 1. Present-day Climate and Woodland Composition). The scenarios are illustrative rather than comprehensive, and do not account for all future uncertainty; they are used here to explore potential outcomes rather than as a predictive tool. Management decisions should also include contingency planning to provide resilience against additional future uncertainties. As such, the examples chosen here are not hard and fast recommendations; for example, future oak regeneration cannot be guaranteed.

1.2.1 Non-Intervention

Drawing on 66 priority lichens (Nature Conservation (Scotland) Act 2004) which occur in Glen Creran SSSI (Annex 1), the study examined risk through to 2080 for Glasdrum. This was done by exploring the processes of (i) woodland succession based on a forward projection of the present-day tree age structure at the site, together with (ii) the effect of climate change scenarios (Scenario 2. Future Climates with No Oak Regeneration). This acknowledges that the impact of local woodland change on epiphyte communities will occur alongside global climate change. We then examined the effect of a catastrophic risk, such as tree disease, using ash dieback as an example (Pautasso *et al.*, 2013), and removing ash trees from the system. This gave us our Scenario 3. Future Climates with No Oak Regeneration, and Ash Dieback.

1.2.2 Intervention

Following from the scenarios presented in Section 1.2.1, we explored alternative woodland management options and considered how these might reduce the risk for priority lichen epiphytes, i.e. the extent to which they could offset a decline in species' environmental suitability. In this study a range of possible management options was discussed at a meeting with SNH (David Genney and Jeanette Hall, personal communication). The first 'intervention' scenario considered how the potential impact of ash dieback might be mitigated by an increase in the proportion of oak, which has previously been shown to support many species of lichen associated with ash (Mitchell et al 2014). Since the future impact of ash-dieback is uncertain, we also considered a scenario in which some ash survives. In order to keep the analysis to a manageable size, we restricted the number of 'intervention' scenarios to two:

- Scenario 4. Future Climates with Oak Regeneration, and Ash Dieback
- Scenario 5. Future Climates with Oak Regeneration, and Ash Survival

It should be noted that these are only a sample of a wide range of possible scenarios, and no assumptions have been made about their relative likelihood.

2. METHODS

Technical aspects of the methods have been described in detail elsewhere (Ellis *et al.*, 2015a), and a summary is provided here.

2.1 Dendrochronology

The dendrochronology analysis was carried out as part of an MSc project at the Royal Botanic Garden Edinburgh (Mulcahy, 2014), and included a representative sample of trees based on the species composition and age structure of woodland at Glasdrum. One hundred and forty-one trees were cored.

The Glasdrum NNR site boundary was projected into ArcMap v. 10 (ESRI, 2012), along with polygons from the Native Woodland Survey of Scotland (NWSS) (Patterson, *et al*. 2014). Each polygon within the NWSS included information on the canopy cover for tree species divided into different maturity classes and associated size categories. These were integrated across the polygons, taking into account the different sizes of individual polygons, to calculate, for Glasdrum, the proportion of trees of a given species, within an associated size category. Each proportion was multiplied by 141 to calculate how many trees of a given species and size category were to be cored (for birch n = 59; alder n = 27, ash n = 27, hazel n = 17, oak n = 10, and elm n = 1). No cores were sampled for those cases where the representative number of sampled trees was calculated to be < 1, i.e. cases which accounted for < 0.75% of the woodland composition (such as for holly, rowan or willows).

The sampled trees were chosen in a manner that accurately reflected the contribution of tree species, accumulated across each NWSS polygon, to the total compositional and demographic woodland structure of the site. Trees of a given species and size category were selected using a random weighting from each polygon, their circumference at 1.3 metres was measured, and they were cored with a Pressler-type tree borer. Cores were stored in plastic straws in the field, and glued and strapped into wooden grooved splints for preparation. Cores were sectioned longitudinally using a scalpel, and were sanded before rings were counted under a dissecting microscope (x10 - x50).

If the centre of the core was not visible, a growth index was calculated based on the average ring width and dividing this into the radius (minus five); if possible, this was cross-referenced in combination with an acetate sheet of evenly spaced concentric circles corresponding to the average ring width, which was aligned to the sectioned core to estimate the age.

Hazel was treated slightly differently to the other tree species. The diameter of a hazel stool was measured around the base; the largest pole associated with a given stool was measured at 1.3 metres, and cored and aged (as above). The age of a stool was very cautiously estimated using protocols advised by Coppins & Coppins (2012), with the age of individual hazel stems providing a simple measure of stem turnover.

2.2 Environmental Suitability

Species-specific models of environmental suitability have been developed, and tested, for 382 lichen epiphytes using the statistical modelling program MAXENT (Ellis *et al.*, 2015a). The model explains the observed distribution of a species, where it occurs as an epiphyte, across Britain (based on British Lichen Society data), in relation to climate, pollution and landscape-scale woodland structure. This provided estimated environmental suitability values for the modelled species, at a 10 km grid-scale for the baseline period of 1961-2010. The models for each lichen epiphyte have also been projected to estimate environmental suitability values for the same location (10 km grid square) in the future. This utilised standard Met Office scenarios of climate change delivered under work programme UKCP09 (Jenkins *et al.*, 2010; Sexton *et al.*, 2010), as well as a changing pollution regime. The pollution regime included declining levels of SO_2, to which lichens are extremely sensitive, though maintained nitrogen levels at recent values (2004-2006) consistent with observed and modelled trends (Fowler *et al.*, 2004; Dentener *et al.*, 2006).

In general terms, climate change scenarios for Scotland indicate warming throughout the year, with shifts in seasonal patterns of precipitation, towards drier summers with longer drought periods, and wetter winters with intense rainfall events. Each scenario of climate change used here - e.g. for the 2050s under a medium greenhouse gas emissions scenario, or for the 2080s under a high emissions scenario - included 11 variants (referred to as an ensemble). The difference between the 11 variants captures a spread of variability in the climate models (Sexton *et al.*, 2010), and represents future climate uncertainty for a given scenario. The uncertainty in climate models emerges because the climate is incredibly complex (simplified into models) and chaotic, so that antecedent conditions can have a strong effect on the final outcome of future estimates.

For each lichen epiphyte the environmental suitability for a given location can be adjusted by a local weighting factor that takes into account woodland composition, and which is constructed based on the lichen epiphyte's known association with different trees (Ellis *et al*., 2015a). In this study, composition at the baseline reflected the proportion that each tree contributes to the present-day woodland structure, and adjustments were then made to the predicted woodland composition based on future scenarios of non-intervention, or intervention (Table 1).

The baseline analysis (Scenario 1 in Table 1) adopted the present-day woodland structure as a reference point. Birch (the commonest tree in the present-day woodland) was given a weighting score of 5, with other trees scaled relative to this. Elm was very rare and was given a score of 0, reflecting a low degree of confidence in its present and future role as substantial epiphytic habitat. Scenario 2 assumed a loss of oak from the woodland, so its weighted score was adjusted from 1 to 0. Scenario 3 also assumed a loss of oak, as in Scenario 2, but also the loss of ash, which was down weighted from 2 to 0.

Table 1. The abundance values (percentages) for trees in the present-day woodland, and the weighting scores (in parentheses) used to modify the environmental suitability values for lichen epiphytes across each of five management scenarios. The weightings for tree species are used in the Lichen Epiphyte Scenarios Toolkit (Ellis et al., 2015a), ranging from a maximum of 5 (near constant canopy component) to a minimum of 0 (absent).

Woodland Scenario [number] Description	**Birch**	**Alder**	**Ash**	**Hazel**	**Oak**	**Elm**
[1] Present-day Climate and Woodland Composition	42% (5)	19% (2)	19% (2)	12% (1)	7% (1)	1% (0)
[2] Future Climates with No Oak Regeneration	(5)	(2)	(2)	(1)	(0)	(0)
[3] Future Climates with No Oak Regeneration, and Ash Dieback	(5)	(2)	(0)	(1)	(0)	(0)
[4] Future Climates with Oak Regeneration, and Ash Dieback	(2)	(2)	(0)	(1)	(4)	(0)
[5] Future Climates with Oak Regeneration, and Ash Survival	(2)	(2)	(3)	(1)	(3)	(0)

Scenarios 4 and 5 captured the effects of regeneration to maintain oak as a significant component in mature woodland stands. Scenario 4 assumed oak dominance by increasing the weighting score from 1 to 4, with birch and alder sub-dominant, such that the weighting of birch was reduced from 5 to 2. Scenario 5 is based on the co-dominance of oak and ash together, with both given a weighting score of 3, and with birch and alder sub-dominant as in Scenario 4.

2.3 Scenario Analysis

Scenario analysis was implemented using the Lichen Epiphyte Scenarios toolkit (Ellis *et al.*, 2015a), which allows the user to explore environmental suitability for lichen epiphytes, across different combinations of baseline conditions or climate change (2050s, 2080s) and woodland tree species composition. To ensure it was fully robust, the MAXENT model, which underpins the scenario analysis, was implemented only for species which occurred in > 30 10 km grid squares in the British Isles, the 48 priority epiphyte species that met this threshold are highlighted in Annex 1.

3. RESULTS AND DISCUSSION

The results are discussed in four sections below, dealing with the trend in historic woodland structure, the baseline environmental suitability of the site for lichen epiphytes, and the scenarios of non-intervention and intervention examples.

3.1 Glasdrum Woodland Structure

Sampling by dendrochronology revealed several key features of the NNR (Figure 2), which can be explained in two developmental stages.

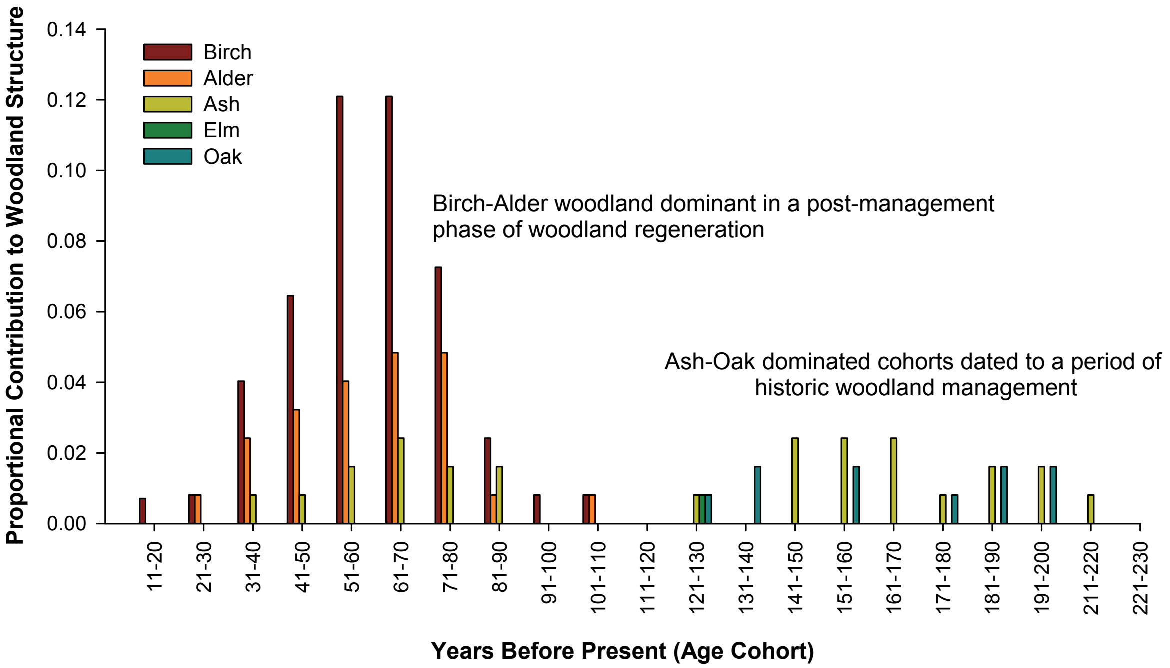

Figure 2. The woodland age profile of Glasdrum, showing tree species grouped into their decadal age cohorts.

3.1.1 Historic Management Phase

First, the age profile of the woodland points to earlier cohorts of mature trees of historic commercial value, which are oak and ash, and which span an age range from *c*. 140-220 yr. This places the origin of the trees from the late 18th Century (*c*. 1790), through to the late 19th Century (*c*. 1870), at a time of organised woodland management at the site (Scottish Natural Heritage, 2013). On this basis, the older trees in the cohort may represent oak or ash standards which are thought to have existed within the site, with the younger trees within this age-range possibly 'singled' coppice that have now grown to maturity. The scarcity of alder and birch dating from this period is characteristic of the simplification of the managed 19th Century woodland. Evidence suggests that alder and birch 'black woods' were cleared from Glasdrum in 1789 for mass conversion to charcoal, and subsequently may not have been protected from grazing (Scottish Natural Heritage, 2013; *cf*. Lindsay, 1974).

3.1.2 Post Management Phase

There is a period from *c*. 100-130 yr ago, when there appears to have been very low recruitment of trees into the ecosystem. This is consistent with the abandonment of active management aimed at ensuring a recurrent supply of oak and ash, leading to a period without enclosure during which grazing by sheep (and/or deer) may have been at a higher intensity across the site, preventing regeneration. Nevertheless, a cohort of more recent woodland appears to have successfully regenerated, with trees spanning the age range from 40-90 yr. This places a second phase of woodland growth in the period from 1920 to 1970, though centred around 1945-1965. The absence of oak regeneration may be explained by its palatability, with alder and birch less attractive to herbivores.

3.1.3 Hazel Dynamics

In contrast to old-growth hazelwoods (Coppins & Coppins, 2012), it is expected that hazel was extensively cut at Glasdrum for charcoal (Scottish Natural Heritage, 2013; cf. Lindsay, 1974) though stems would have regenerated from what may be ancient stools at the site (Figure 3). Although the stools may be old (spanning an estimated age range of 100 to > 500 years), the individual hazel stems do not grow old and form a separate cohort nested within the age range of the stools themselves (Figure 3); there is therefore a relatively rapid turnover of stem material within a long-lived stool.

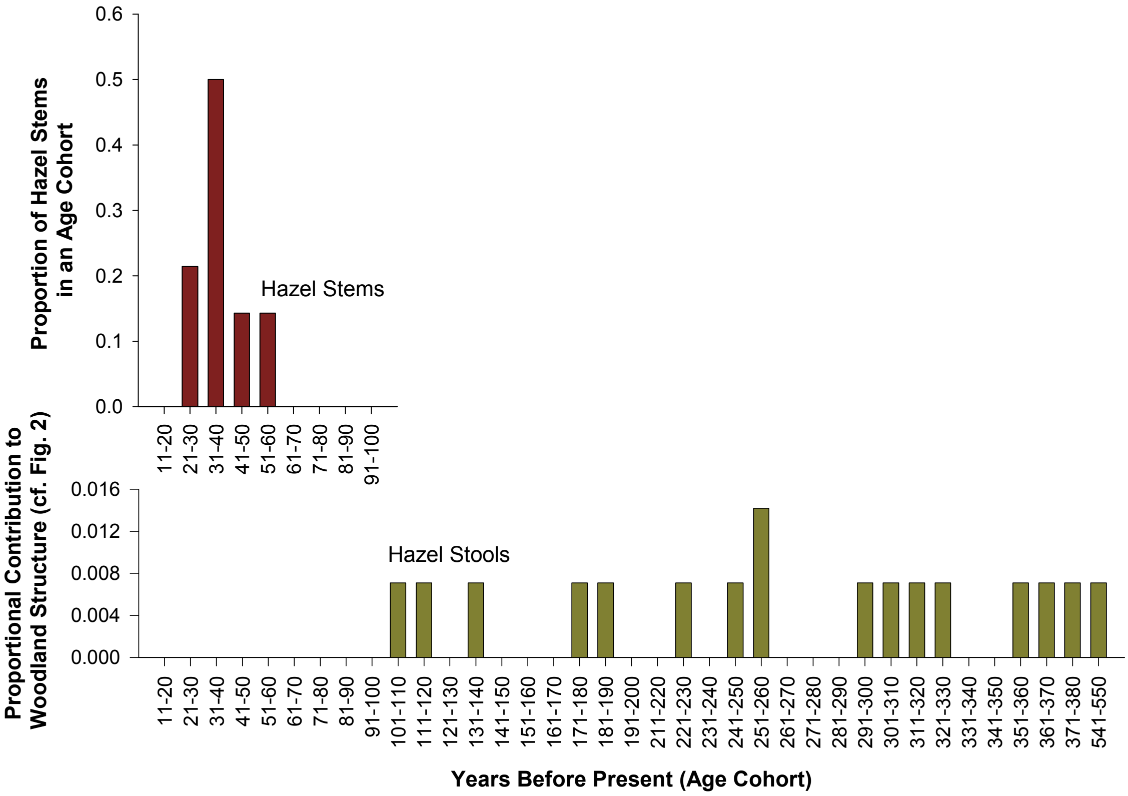

Figure 3. The contribution of hazel stools (estimated age: cf. Coppins & Coppins, 2012), to the woodland structure (cf. Figure 2), and the proportion of individual hazel stems (largest stem per stool) in a given age cohort.

3.2 Baseline Analysis

The baseline analysis (Scenario 1 in Table 1) adopted the present-day woodland structure as a reference point, combined with the present-day climate, and calculated environmental suitability for the 48 priority lichen epiphyte species that had been statistically modelled (Annex 1). This formed the starting point for cross-reference with future scenarios, and was used to identify opportunities to maintain or improve environmental suitability values for priority species (Figure 4).

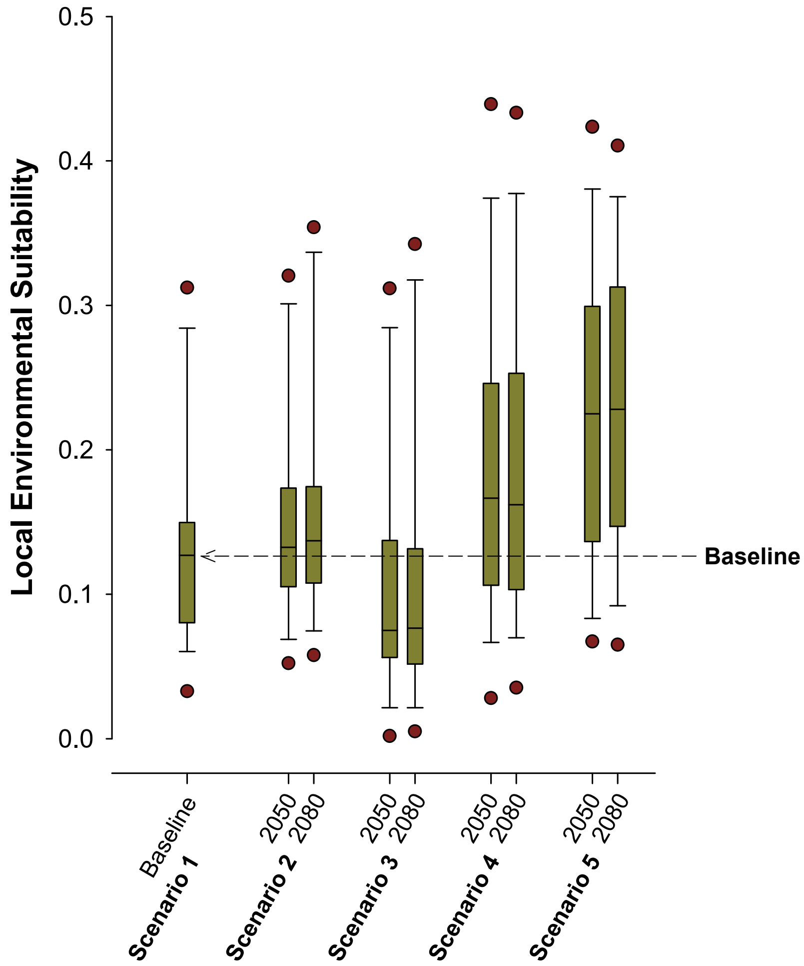

Figure 4. Boxplots (median, 25th-75th, 10th-90th and 5th-95th percentiles) to summarise the local environmental suitability for the 48 modelled priority species under the different climatic and woodland change scenarios outlined in Table 1.

3.3 Non-Intervention Scenarios

The analysis of present-day woodland structure (Figures 2 & 3) leads to two scenarios of non-intervention (Table 1).

Our first non-intervention scenario (Scenario 2) develops from the lack of recent oak regeneration relative to the proportion of mature trees. Projecting this forward results in a woodland structure in the 2050s and 2080s that would be severely depleted in oak, and would consist of alder, ash and birch in proportions equivalent to their present-day status (Table 1). In this case there is little difference in terms of the epiphyte environmental suitability compared to the baseline environment (Figure 4). Oak is a relatively minor component of the woodland currently, and two factors mitigate the effect of further oak decline on lichens in this scenario: (i) oak shares an overlapping epiphyte flora with ash (Ellis *et al.*, 2013) which in Scenario 2 persists over the long-term and to some extent can act as a substitute habitat, and (ii) the climate change effect on oceanic lichen species has been shown for standard modelled scenarios to be mixed and often positive (Ellis *et al.*, 2007), so long as the warming climate remains sufficiently wet (Jenkins *et al.*, 2010). The loss of oak may be offset by an ameliorating climate.

Scenario 3 includes a loss of oak from the woodland, as in Scenario 2, but also the loss of ash resulting from ash dieback (Pautasso *et al.*, 2013). This loss of both oak and ash for the 2050s and 2080s is projected to have a strong negative effect on the priority epiphyte species, with values of environmental suitability declining significantly (by 40-42%) below the present-day baseline (Figure 4). The scenario of combined oak and ash decline highlights a significant potential risk to the lichen biodiversity of Glasdrum.

3.4 Intervention Scenarios

Scenarios 4 and 5 capture the key intervention of actively increasing the amount of oak regeneration, in order to maintain oak as a significant component in mature woodland stands (Table 1). No assumption is made as to whether this intervention would in practice be successful in increasing the amount of oak, highlighting the importance of contingency planning.

Scenario 4 demonstrates that shifting the woodland from a birch-alder dominated structure, to one in which oak is dominant, with birch and alder sub-dominant, has the critically important effect of partly off-setting the effect of ash dieback on epiphytic lichens should this disease become a threat (Figure 4). Scenario 5 is the best scenario of those considered for the priority epiphyte species, with the highest values of environmental suitability (77-79% increase over the baseline), based on the co-dominance of oak and ash (regenerating oak, and resisting ash dieback), with birch and alder sub-dominant (Figure 4).

3.5 Species Responses

Annex I can be used alongside the general trends presented for each of the scenarios (cf. Figure 4) to cautiously examine the response for individual priority species. Many species follow the general trends presented in Figure 4, though some exceptions highlight the fact that during the process of habitat management and larger-scale environmental change there can be winners and losers.

For example, species such as *Micarea synotheoides* and *Pertusaria opthalmiza* show a decline in environmental suitability for Scenario 2, which is not offset by scenarios with increasing oak and ash (such as in Scenario 5). This may be because these species tend to be more common in relatively acidic microhabitats, and so the projected shift in habitat structure for Scenario 5 (which includes a lower weighting for birch) does not compensate for a negative effect of climate change. For other species such as *Fuscopannaria sampaiana*, Scenario 2 results in a slight increase in environmental suitability (explained by climate warming), but with a relatively large increase in environmental suitability for Scenario 5, related to the combined positive effect of climate and woodland structure, especially an increase in ash.

Annex I can also be used to understand how the pathway of climate change can alter decision-making for biodiversity, as well as exploring uncertainty in the climate models.

In terms of the pathway of climate change it is the comparison between time-slices that matters (2050s and 2080s). For some species, the progression of climate change appears to be positive, with increasing environmental suitability from the 2050s to the 2080s (e.g. *Hypotrachyna taylorensis*). For other species climate change scenarios may be positive in the mid-term and negative in the longer-term (e.g. *Parmeliella testacea*). For others there seems to be little sensitivity (e.g. *Bacidea caesiovirens* and *Leptogium cyanescens*) to climate, with no substantial difference among the time-slices.

In terms of uncertainty in the climate models, it is the range in projected environmental suitability values that matters. For species such as *Gomphillus calycioides* or *Menegazzia terebrata*, the estimated shift in environmental suitability for an individual scenario can be below (worsening) or above (improving) the baseline value (see for example Scenario 2), indicating that the projection for these species depends on the choice of 'best estimate' of future climate, with the best estimates (i.e. variants in the climate ensemble) considered equally plausible. For other species, such as *Hypotrachyna sinuosa* or *Pseudocyphellaria crocata*, the estimated shift is above the baseline value for all variants and time-slices, providing greater overall confidence in the species' response to climate change, even with the change in tree species composition being considered.

The details of the modelled response for different species could be used to target population monitoring to the most 'at risk' species, including assessing adaptation actions aimed at reducing the vulnerability of species that are exposed to the negative impacts of climate change. It would in time also be possible to adjust the statistical projections of climate change response by monitoring across the 'winners' and 'losers', ultimately leading to an improved understanding of the impacts of climate change on biodiversity.

4. CONCLUSIONS

Given the site history of Glasdrum which suggests a likely decline in oak, non-intervention scenarios present the worst options for epiphyte diversity, especially given the additional threat of ash dieback.

Active management towards a greater structural and tree species diversity including oak regeneration (i) improves the general estimation of environmental suitability for most of the priority lichen epiphyte species, compared to a system in which oak is lost, and (ii) could help to offset the potential negative effect of ash dieback, should this become an issue, by providing a substitute habitat for many of the epiphytes which may otherwise also occur on ash.

The scenario approach described here could be used to inform contingency planning, recognising that it may not be possible to manage future woodland tree composition in a predictable way, e.g. due to uncertain responses to climate change.

This report focusses on epiphytic lichens as a case-study to demonstrate a scenario approach to long-term management. Lichens only represent one aspect of the interest of Glasdrum NNR, and the impact on, and requirements of, other features should also be considered in developing proposals for management of the reserve.

4.1 Follow-Up Work

This project has quantified and can support the benefits of woodland diversification (including the regeneration of oak) in creating habitat that is suitable for priority lichen epiphyte species, and as an 'insurance policy' in providing resilience against ash dieback. It represents the application of scenario analysis using a publicly available toolkit (Ellis *et al.*, 2015a: Figure 5), which could be applied across a wide range of site and management contexts; extensive testing has demonstrated that the toolkit can resolve the variable consequences of climate and woodland change for different sites (Ellis *et al*., 2015b).

However, a study of this type represents a broad assessment based on 'averaged' effects of shifts in woodland tree species composition. The suitability of a woodland for priority epiphytes does not depend only on the tree species composition but also on the availability of suitable microhabitats, e.g. in terms of the canopy openness, or ensuring a sufficient number of trees across contrasting topographic positions and with different structural attributes. This requirement for microhabitat detail is now the subject of an SNH-SEPA funded PhD (*Achieving Landscape-Scale Conservation of Scotland's Rainforest Epiphytes*), which is examining the niche requirements of nine target epiphyte species within Glen Creran, and aiming to optimise the spatial configuration of suitable niche space in order to maintain population viability of target lichen epiphytes.

Scenario analysis provides an important tool to allow woodland managers to better understand the potential consequences of their decisions. This approach is particularly important for woodland management where, due to the longevity of trees, current decisions to deliver priority outcomes may take many years to come to fruition. Further work is, however, required to help managers choose the most appropriate range of scenarios to explore. For example, the illustrative scenarios explored here are a small subset of possibilities and based on assumptions as to what an uncertain future may hold. In our changing environment we need to move towards new ways of long-term decision making that do not rely on business-as-usual assumptions. Scenario analysis will contribute to this process, along with other tools, and will enable a move towards a contingency planning approach that accounts for uncertainty and unknowable factors.

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ANNEX 1: THE LIST OF 66 PRIORITY LICHENS DOWNLOADED FROM THE NATIONAL BIODIVERSITY NETWORK (NBN GATEWAY), WITHIN OR OVERLAPPING THE SITE BOUNDARY OF GLASDRUM SSSI

Note that some lichen species are known to occur at the site, but are not included on this list (e.g. *Pannaria conoplea & P. rubiginosa*). For consistency we used the available NBN data rather than supplementing with personal observations (British Lichen Society mapping scheme data at a 100 m resolution, 1700-2011 - downloaded October 2014).

Environmental suitability values for 48 of the priority lichen epiphyte species are shown for the five contrasting scenarios (*cf*. Table 1). Scenarios 2-5 include the range of projected environmental suitability values (for different climate model variants = climatic uncertainty) followed by the mean calculated among the variants.

Priority Species	**SCENARIOS**								
	1	**2**		**3**		**4**		**5**	
	BASE	**2050s**	**2080s**	**2050s**	**2080s**	**2050s**	**2080s**	**2050s**	**2080s**
Anisomeridium viridescens	0.14	0.149-0.169, 0.160	0.141-0.178, 0.161	0.146-0.166, 0.158	0.139-0.176, 0.159	0.167-0.190, 0.180	0.158-0.200, 0.181	0.163-0.186, 0.176	0.155-0.196, 0.177
Arthonia ilicina	0.079	0.095-0.141, 0.118	0.118-0.147, 0.137	0.075-0.111, 0.093	0.093-0.116, 0.108	0.085-0.125, 0.105	0.105-0.130,0.121	0.110-0.162, 0.136	0.136-0.169, 0.157
Arthopyrenia carneobrunneola	0.07	0.073-0.153, 0.116	0.092-0.149, 0.121	0.062-0.130, 0.099	0.078-0.127, 0.103	0.074-0.155, 0.118	0.093-0.151, 0.123	0.087-0.182, 0.138	0.110-0.178, 0.144
Arthopyrenia nitescens	0.054	0.091-0.130, 0.113	0.116-0.134, 0.129	0.089-0.128, 0.110	0.114-0.131, 0.127	0.104-0.149, 0.129	0.134-0.154, 0.148	0.103-0.148, 0.128	0.132-0.152, 0.147
Arthothelium macounii	Not modelled								
Bacidia caesiovirens	0.135	0.050-0.097, 0.073	0.046-0.102, 0.072	0.043-0.084, 0.063	0.039-0.088, 0.062	0.069-0.136, 0.103	0.064-0.142, 0.100	0.067-0.132, 0.100	0.062-0.138, 0.097
Bactrospora homalotropa	0.062	0.044-0.099, 0.069	0.058-0.111, 0.089	0.034-0.077, 0.053	0.045-0.086, 0.069	0.051-0.114, 0.079	0.067-0.129, 0.103	0.062-0.138, 0.095	0.081-0.155, 0.124
Calicium lenticulare	Not modelled								
Caloplaca ferruginea	Not modelled								
Cladonia cenotea	Not modelled								
Collema subnigrescens	Not modelled								
Dictyonema interruptum	Not modelled								

Fuscopannaria sampaiana	0.125	0.183-0.197, 0.190	0.163-0.198, 0.187	0.054-0.058, 0.056	0.048-0.058, 0.055	0.212-0.228, 0.219	0.189-0.229, 0.216	0.366-0.393, 0.379	0.326-0.396, 0.373
Gomphillus calycioides	0.146	0.060-0.209, 0.133	0.087-0.231, 0.176	0.029-0.099, 0.063	0.041-0.110, 0.084	0.052-0.181, 0.115	0.075-0.200, 0.152	0.092-0.318, 0.203	0.132-0.352, 0.268
Graphina ruiziana	0.1	0.083-0.115, 0.098	0.095-0.122, 0.111	0.075-0.103, 0.088	0.086-0.110, 0.100	0.190-0.262, 0.223	0.218-0.279, 0.254	0.169-0.234, 0.199	0.194-0.249, 0.226
Gyalideopsis muscicola	0.09	0.126-0.142, 0.136	0.126-0.143, 0.138	0.072-0.081, 0.077	0.072-0.081, 0.079	0.226-0.254, 0.243	0.225-0.255, 0.247	0.265-0.298, 0.285	0.263-0.299, 0.289
Hypotrachyna endochlora	0.319	0.268-0.364, 0.311	0.272-0.383, 0.348	0.245-0.332, 0.284	0.249-0.349, 0.317	0.261-0.354, 0.303	0.265-0.373, 0.339	0.259-0.351, 0.300	0.263-0.369, 0.336
Hypotrachyna sinuosa	0.226	0.306-0.337, 0.321	0.318-0.341, 0.336	0.294-0.324, 0.309	0.306-0.328, 0.323	0.235-0.259, 0.247	0.244-0.262, 0.258	0.229-0.252, 0.241	0.238-0.256, 0.252
Hypotrachyna taylorensis	0.248	0.160-0.256, 0.213	0.132-0.261, 0.214	0.149-0.237, 0.197	0.122-0.242, 0.199	0.280-0.446, 0.371	0.230-0.456, 0.374	0.245-0.391, 0.325	0.202-0.400, 0.328
Lecania cyrtella	0.051	0.022-0.094, 0.041	0.032-0.109, 0.075	0.002-0.006, 0.003	0.002-0.007, 0.005	0.009-0.037, 0.016	0.012-0.043, 0.029	0.038-0.160, 0.070	0.054-0.185, 0.127
Lecanora cinereofusca	Not modelled								
Leptogium brebissonnii	0.08	0.082-0.140, 0.112	0.038-0.147, 0.112	0.066-0.111, 0.089	0.030-0.117, 0.089	0.091-0.155, 0.124	0.042-0.163, 0.124	0.109-0.185, 0.148	0.050-0.195, 0.148
Leptogium burgessii	0.132	0.057-0.141, 0.103	0.049-0.144, 0.107	0.026-0.064, 0.047	0.022-0.065, 0.049	0.040-0.098, 0.072	0.034-0.100, 0.075	0.083-0.204, 0.149	0.071-0.208, 0.155
Leptogium cochleatum	Not modelled								
Leptogium cyanescens	0.08	0.094-0.168, 0.138	0.095-0.168, 0.137	0.046-0.083, 0.068	0.047-0.083, 0.068	0.081-0.145, 0.119	0.082-0.145, 0.118	0.142-0.254, 0.209	0.143-0.254, 0.207
Leptogium hibernicum	Not modelled								
Leptogium intermedium	Not modelled								
Lobaria amplissima	0.134	0.106-0.133, 0.123	0.105-0.124, 0.116	0.032-0.041, 0.037	0.032-0.038, 0.035	0.228-0.286, 0.265	0.225-0.267, 0.250	0.289-0.363, 0.335	0.285-0.338, 0.317
Lobaria pulmonaria	0.155	0.143-0.157, 0.151	0.146-0.155, 0.151	0.069-0.076, 0.073	0.070-0.074, 0.073	0.215-0.236, 0.227	0.220-0.232, 0.227	0.285-0.313, 0.300	0.291-0.307, 0.300
Lobaria scrobiculata	0.151	0.114-0.143, 0.132	0.111-0.144, 0.133	0.074-0.092, 0.085	0.071-0.093, 0.086	0.191-0.239, 0.221	0.185-0.241, 0.223	0.216-0.271, 0.250	0.210-0.272, 0.252
Lobaria virens	0.126	0.098-0.141, 0.127	0.093-0.126, 0.110	0.052-0.075, 0.067	0.049-0.067, 0.058	0.166-0.240, 0.216	0.158-0.215, 0.188	0.204-0.293, 0.265	0.193-0.263, 0.230
Megalospora tuberculosa	0.129	0.159-0.170, 0.166	0.168-0.171, 0.170	0.015-0.016, 0.016	0.016-0.017, 0.016	0.275-0.294, 0.287	0.289-0.295, 0.293	0.424-0.453, 0.442	0.446-0.455, 0.452

Melaspilea atroides	0.061	0.095-0.170, 0.128	0.126-0.182, 0.159	0.079-0.141, 0.107	0.105-0.151, 0.132	0.085-0.151, 0.114	0.112-0.161, 0.141	0.107-0.191, 0.145	0.142-0.205, 0.179
Menegazzia terebrata	0.304	0.200-0.382, 0.300	0.272-0.396, 0.359	0.194-0.370, 0.290	0.263-0.383, 0.347	0.177-0.337, 0.264	0.240-0.349, 0.317	0.166-0.317, 0.249	0.226-0.328, 0.298
Micarea alabastrites	0.304	0.299-0.341, 0.320	0.317-0.367, 0.343	0.294-0.335, 0.314	0.311-0.361, 0.337	0.312-0.355, 0.334	0.331-0.383, 0.358	0.277-0.316, 0.297	0.294-0.340, 0.318
Micarea stipitata	0.358	0.312-0.409, 0.368	0.310-0.414, 0.380	0.306-0.401, 0.361	0.305-0.407, 0.373	0.343-0.449, 0.404	0.341-0.456, 0.418	0.301-0.395, 0.355	0.300-0.400, 0.367
Micarea synotheoides	0.282	0.115-0.171, 0.155	0.094-0.159, 0.138	0.109-0.162, 0.146	0.089-0.150, 0.130	0.132-0.196, 0.177	0.107-0.182, 0.158	0.120-0.179, 0.161	0.098-0.166, 0.144
Micarea xanthonica	0.268	0.243-0.259, 0.253	0.230-0.252, 0.244	0.243-0.259, 0.253	0.230-0.252, 0.244	0.444-0.474, 0.464	0.421-0.462, 0.446	0.360-0.384, 0.376	0.341-0.374, 0.361
Nephroma laevigatum	0.112	0.125-0.143, 0.133	0.116-0.135, 0.128	0.053-0.061, 0.057	0.050-0.057, 0.054	0.145-0.166, 0.155	0.135-0.156, 0.148	0.227-0.260, 0.243	0.212-0.245, 0.232
Parmeliella parvula	0.199	0.188-0.227, 0.212	0.201-0.229, 0.219	0.155-0.186, 0.174	0.165-0.188, 0.180	0.277-0.334, 0.311	0.295-0.338, 0.322	0.279-0.335, 0.313	0.297-0.340, 0.324
Parmeliella testacea	0.129	0.130-0.194, 0.176	0.033-0.188, 0.129	0.062-0.093, 0.084	0.016-0.090, 0.061	0.105-0.157, 0.142	0.027-0.152, 0.104	0.195-0.291, 0.263	0.050-0.282, 0.193
Parmeliella triptophylla	0.142	0.133-0.150, 0.141	0.113-0.150, 0.137	0.042-0.047, 0.044	0.036-0.047, 0.043	0.149-0.168, 0.159	0.127-0.169, 0.155	0.258-0.290, 0.274	0.220-0.291, 0.267
Peltigera collina	0.128	0.097-0.143, 0.121	0.067-0.104, 0.087	0.041-0.061, 0.051	0.028-0.044, 0.037	0.093-0.137, 0.116	0.064-0.099, 0.084	0.163-0.240, 0.204	0.113-0.174, 0.147
Pertusaria ophthalmiza	0.265	0.190-0.244, 0.231	0.166-0.248, 0.219	0.190-0.244, 0.231	0.166-0.248, 0.219	0.143-0.184, 0.174	0.125-0.187, 0.166	0.129-0.165, 0.157	0.112-0.168, 0.149
Phyllopsora rosei	0.137	0.083-0.106, 0.095	0.077-0.108, 0.095	0.019-0.025, 0.022	0.018-0.025, 0.022	0.357-0.453, 0.409	0.329-0.462, 0.409	0.367-0.466, 0.422	0.339-0.476, 0.421
Pseudocyphellaria crocata	0.081	0.107-0.133, 0.119	0.119-0.136, 0.129	0.093-0.116, 0.104	0.104-0.119, 0.113	0.139-0.173, 0.156	0.155-0.177, 0.168	0.145-0.180, 0.162	0.162-0.184, 0.175
Pseudocyphellaria intricate	0.077	0.030-0.116, 0.066	0.024-0.096, 0.065	0.017-0.066, 0.037	0.014-0.055, 0.037	0.020-0.076, 0.043	0.016-0.063, 0.043	0.039-0.148, 0.084	0.030-0.123, 0.083
Pseudocyphellaria norvegica	0.083	0.053-0.139, 0.095	0.033-0.128, 0.083	0.033-0.086, 0.059	0.020-0.079, 0.051	0.051-0.134, 0.092	0.032-0.123, 0.080	0.075-0.200, 0.136	0.047-0.183, 0.119
Ptychographa xylographoides	Not modelled								
Pyrenula hibernica	Not modelled								
Pyrenula laevigata	0.062	0.032-0.113, 0.066	0.030-0.070, 0.052	0.031-0.111, 0.064	0.029-0.068, 0.051	0.031-0.109, 0.063	0.029-0.067, 0.050	0.032-0.113, 0.065	0.030-0.069, 0.052

Pyrenula occidentalis	0.098	0.065-0.105, 0.085	0.067-0.087, 0.078	0.053-0.086, 0.070	0.055-0.071, 0.064	0.063-0.101, 0.083	0.065-0.084, 0.076	0.077-0.125, 0.101	0.080-0.103, 0.093
Ramalina fraxinea	0.007	0.002-0.009, 0.004	0.001-0.054, 0.032	0.000-0.001, 0.001	0.000-0.009, 0.005	0.001-0.004, 0.002	0.001-0.026, 0.015	0.004-0.015, 0.007	0.002-0.089, 0.052
Rinodina isidioides	Not modelled								
Schismatomma quercicola	0.13	0.141-0.157, 0.153	0.146-0.159, 0.153	0.138-0.153, 0.149	0.143-0.155, 0.150	0.455-0.507, 0.492	0.471-0.513, 0.494	0.365-0.407, 0.395	0.378-0.412, 0.396
Spilonema paradoxum	Not modelled								
Sticta fuliginosa	0.122	0.134-0.161, 0.150	0.147-0.164, 0.158	0.074-0.088, 0.082	0.081-0.090, 0.087	0.156-0.187, 0.174	0.171-0.191, 0.184	0.221-0.266, 0.247	0.243-0.271, 0.262
Sticta limbata	0.117	0.106-0.129, 0.122	0.112-0.129, 0.121	0.055-0.067, 0.064	0.058-0.067, 0.063	0.196-0.236, 0.225	0.206-0.237, 0.222	0.236-0.285, 0.271	0.248-0.286, 0.268
Sticta sylvatica	0.138	0.121-0.150, 0.133	0.130-0.155, 0.145	0.055-0.068, 0.061	0.059-0.071, 0.066	0.159-0.197, 0.175	0.171-0.204, 0.190	0.230-0.283, 0.252	0.246-0.294, 0.274
Strangospora microhaema	Not modelled								
Thelotrema macrosporum	0.104	0.087-0.168, 0.128	0.108-0.163, 0.145	0.075-0.146, 0.111	0.093-0.141, 0.126	0.074-0.145, 0.110	0.093-0.140, 0.125	0.091-0.176, 0.134	0.113-0.170, 0.152
Thelotrema petractoides	0.103	0.038-0.108, 0.075	0.058-0.109, 0.080	0.035-0.099, 0.069	0.054-0.100, 0.074	0.034-0.097, 0.067	0.052-0.097, 0.072	0.038-0.109, 0.076	0.059-0.110, 0.081
Toninia squalida	Not modelled								
Trapeliopsis viridescens	Not modelled								
Trimmatothele perquisite	Not modelled								
Wadeana dendrographa	0.018	0.215-0.253, 0.242	0.209-0.251, 0.227	0.001-0.001, 0.001	0.001-0.001, 0.001	0.074-0.087, 0.083	0.072-0.086, 0.078	0.376-0.443, 0.425	0.367-0.439, 0.398

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