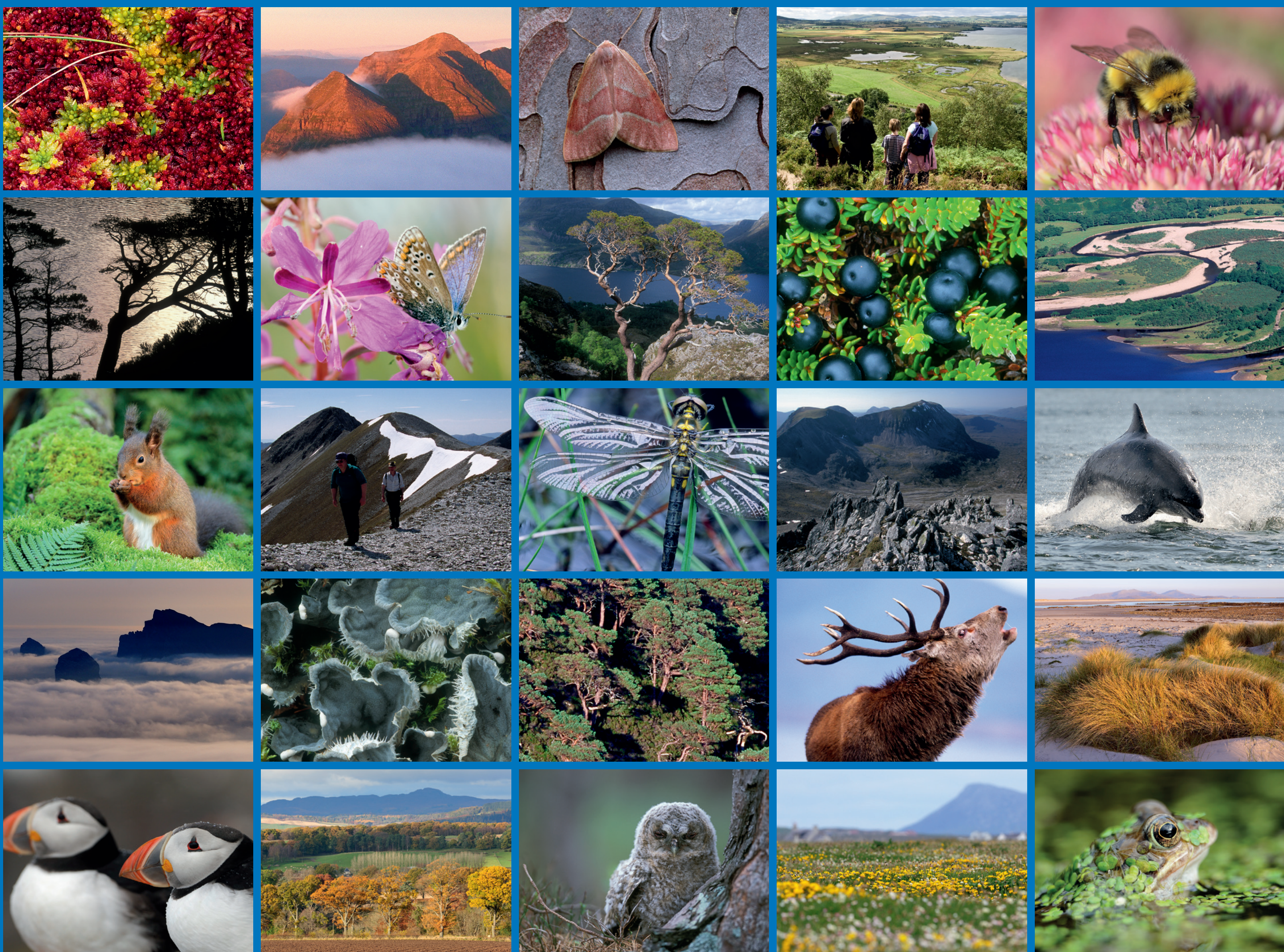
Scottish Natural Heritage
Commissioned Report No. 913

Feasibility study: translocation of species for the establishment or protection of populations in northerly and/or montane environments



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

Commissioned Report No. 913

Feasibility study: translocation of species for the establishment or protection of populations in northerly and/or montane environments

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COMMISSIONED REPORT

Summary

Feasibility study: translocation of species for the establishment or protection of populations in northerly and/or montane environments

Commissioned Report No. 913
Project No: 7966
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Keywords

Arctic; alpine; climate change; conservation translocations; habitat modelling; lichens; mountain.

Background

Climate change is predicted to have very substantial impacts on biodiversity, in some cases driving species to extinction when they are unable to track suitable climatic conditions. This is a particular threat for alpine species, given both the strong control on them exerted by climatic conditions and the increasing isolation of alpine species at higher altitudes. Translocations have been proposed as a technique for helping to conserve such species, if threatened during climate change. However, a substantial literature review undertaken as part of this project highlighted a number of uncertainties associated with their application.

We used a combination of field survey and experimental translocations of an arctic-alpine lichen species *Flavocetraria nivalis* within the Cairngorms. We explored whether it is possible to develop a model to predict the location of suitable habitat for this species (including whether this model indicates a clear influence of climatic variables on the species' distribution) both within its current range and also at sites outside of its range. Although we were able to develop a model with some predictive ability, the power of the model was relatively limited, not least because of the strong impact of small-scale micro-environmental variability which was hard to encompass in the modelling process. Our work also showed that the fit of the model improved through time, as the distribution of transplanted lichens came to more closely match the distribution of suitable environmental conditions for this species.

Main findings

- When translocating immobile species that are likely to be strongly influenced by the abiotic environment, a combination of modelling (based on distribution data) and expert judgement is likely to be an effective way of selecting recipient sites. Within a broader area selected through modelling, expert judgement will allow localised tailoring of the final location of a transplant to best meet the species' requirements.

- Successful translocations for this type of species might also necessitate the movement of a large number of transplants in order to overcome the problem of high mortality due to the strong but complex influence of localised environmental conditions.

- When dealing with this type of species, it is very unlikely that we can develop accurate forward projections of the future spatial location of suitable habitat and environmental conditions. A pragmatic and flexible approach to their conservation under climate change may be needed, including establishing new populations at a range of locations, and repeating translocations through time.

- Long-term monitoring is essential for assessing whether or not conservation translocations of slow-growing and slow-responding species such as arctic-alpine lichens have been a success.

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Acknowledgements

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We would particularly like to thank Invercauld Estate, who kindly hosted the main translocation trial in the Gairn catchment and gave access to Glas Maol for the wider vegetation survey, and all the SNH staff that helped with access to the Allt á Mharcaidh catchment and Creag Meagaidh sites, as well as the paperwork necessary for the various translocation trials.

We are grateful to the British Lichen Society and its members, past and present, who provided baseline data on the distribution of the focal species, *Flavocetraria nivalis* via the National Biodiversity Network Gateway.

We would finally like to thank all of our colleagues from The James Hutton Institute and the Royal Botanic Garden Edinburgh that helped with the very considerable amount of fieldwork involved in this project.

1. INTRODUCTION

1.1 Background

Climate change is one of the major threats to global biodiversity (Hannah *et al.*, 2002; Hoegh-Guldberg *et al.*, 2008). Changes in climatic conditions alter the suitability of environments for species, and under future climate scenarios the occurrence of suitable climatic conditions may or may not overlap with a species' current range. Even if some parts of a species' current range and the location of future suitable climatic conditions overlap, the degree of overlap is likely to be highly variable between species.

Changes in the location of suitable climatic conditions may cause species range-shifting, as species attempt to track suitable climate through space. However, other environmental change drivers such as land use change and associated habitat fragmentation, as well as inherent characteristics of the species such as their rate of reproduction and dispersal mode, may place substantial limitations on the ability of species to track suitable climate. Consequently some species may become 'stranded', i.e. unable to reach those regions where suitable future climatic conditions exist. This has led to the proposed use of species translocations as a tool by which conservationists can overcome this stranding effect. Put most simply, species at risk would be moved from their current locations to those areas expected to be suitable for their growth under future climate change scenarios. However, although an apparently simple concept, there is considerable debate concerning the application of translocation as a conservation tool for dealing with the threat of climate change (Ricciardi & Simberloff, 2009; Thomas, 2011). Translocation should always be considered against the other seven adaptation principles outlined in SNH's climate change action plan (Scottish Natural Heritage, 2016).

The issues associated with the use of translocations are directly relevant to species conservation in Scotland. There is concern that climate change represents a considerable threat to a wide range of Scottish species (Brooker *et al.*, 2004). In addition, habitat fragmentation and the barriers that this places on dispersal have also been identified as a key conservation issue in Scotland (Brooker *et al.*, 2011).

1.2 Aims and structure of this report

Given the necessity of developing conservation management actions relevant to the threats posed by climate change, and the uncertainty associated with the application of species translocations for conservation management, there is clearly a need to better understand the pros and cons of species translocation. This is required to inform when it might be appropriate and feasible to apply. Delivering this improved understanding is a general goal for this project, the overall aim of which is to examine the application of species translocations as a conservation tool for the establishment or protection of populations in northerly and/or montane environments.

The project has been undertaken in two stages. The initial stage involved a wide-ranging literature review (Brooker *et al.*, 2011) which considered the debate concerning species translocations and climate change, and the application of the technique to three species groups: lichens and bryophytes, vascular plants, and invertebrates. The literature review provided an overview of the debate, a summation of commonalities or clear differences between the possible use of translocation for the three species groups, and raised a number of research questions that might be addressed by an experimental study.

This report focuses on the second stage of the project, specifically experimental field-trials of species translocations. These field trials ran from 2010 – 2015 and were aimed at addressing a number of questions highlighted by the literature review, in particular undertaking '*Practical trials of transplant methodologies for particular species groups, e.g.*

terricolous and saxicolous lichen species…. Any field trials should be carried out with properly replicated, statistically sound methodologies and long term monitoring'. Within this wider context, the field trials assessed two more specific questions:

Question 1 - Is it possible to develop a model to predict the location of suitable habitat for the translocated species, and does this model include climate parameters as key factors regulating the species' distribution? If it is not possible to develop a model that is capable of predicting the location of suitable habitat for a species under the current climate, then our ability to predict (at least through statistical modelling) the location of suitable recipient sites for a translocated species under a future climate is likely to be very low. In addition if the factors shown as important in regulating a species' distribution do not include climate, then there is no way to link the species distribution model to future climate projections.

Question 2 – Is it possible to apply this model to detect suitable habitat for a species outside its current Scottish distribution? This provides an additional test for any model of habitat suitability.

1.3 Approach

1.3.1 Target species

We chose to address these questions using a trial translocation of the arctic-alpine lichen *Flavocetraria nivalis. Flavocetraria nivalis* is a fruticose (shrubby), terricolous (ground-dwelling) arctic-alpine lichen that normally occurs above 700 m altitude in Britain (Figure 1). It is associated with lichen-moss heaths in *Calluna-Vaccinium uliginosum-Empetrum-Salix herbacea* plant communities, and avoids areas of late snow-lie (Smith *et al.*, 2009).

The branched lobes of the lichen become firmly entangled within the low-growing shrubby vegetation. Apothecia have never been reported in Britain and dispersal here is thought to be limited to thallus fragmentation and transport. Consequently, movement of adult thalli is likely to be a reasonable approach to translocating this species.

There are a number of reasons why *F. nivalis* is a suitable focal species for this study. First, the species is known to have a distribution within the Scottish mountains that is strongly regulated by abiotic (e.g. climatic) environmental drivers (Crabtree & Ellis, 2010), thereby increasing the possibility that we might develop climate-related predictive models of suitable habitat locations. Second, although capable of dispersing over very large distances at evolutionary time-scales (Geml *et al.*, 2010), individuals of *F. nivalis* are immobile and the relatively rapid pace of climate change (compared to rates of dispersal) and restricted range of the species in Scotland may present a risk at a regional scale; thus *F. nivalis* is a species for which the threat of climate change is relevant. Third, a very large part of the biodiversity of Scotland, and of many other areas globally (including arctic and antarctic environments and oceanic mountain systems), comprises lichens and bryophytes, and so the species is representative of other similar species. Finally, the species is readily identifiable and – for a lichen – comparatively easy to spot, thus making fieldwork more straightforward.

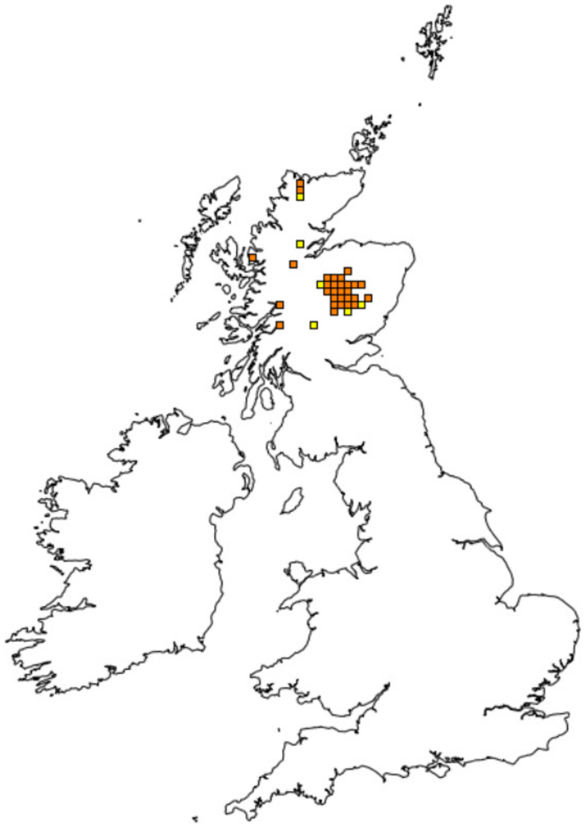

Figure 1. The focal study species Flavocetraria nivalis *(left) and a map of 10 km squares with records for* Flavocetraria nivalis *in Great Britain and Ireland, with yellow squares indicating records for the date range 1600-1959, and orange squares 1960-2016. Photograph courtesy of D. Genney, SNH. Map courtesy of National Biodiversity Network using data provided by the British Lichen Society (BLS) (the BLS, Original Recorder and the NBN Trust bear no responsibility for any further analysis or interpretation of that material, data and/or information). © Crown copyright and database rights 2016 Ordnance Survey [100017955]*

1.3.2 Major components of the field study

There are three major components to the field study. These are:

1. A distribution survey of *F. nivalis* to provide the data needed to develop a predictive training model of the location of suitable habitat.

2. A test of the model using experimental translocations at a study site within the species' current range.

3. A test of the model at a study site outside of the species' current range.

To make this report easier to follow, the Methods and Results sections will deal separately with each of these major components. The Discussion section synthesises data from across the three components, relating the findings to the initial research questions, and developing recommendations for future species translocation practice.

2. METHODS

2.1 *Flavocetraria nivalis* field survey and development of training model

2.1.1 Field survey

A field survey of five sites was undertaken to provide data for modelling the natural distribution of *F. nivalis.* These sites were all located within the lichen's core range based on the data presented in Figure 1. Details of the five sites, including location and sampling date are given in Annex 1; the distribution of the five sites is shown in Figure 2.

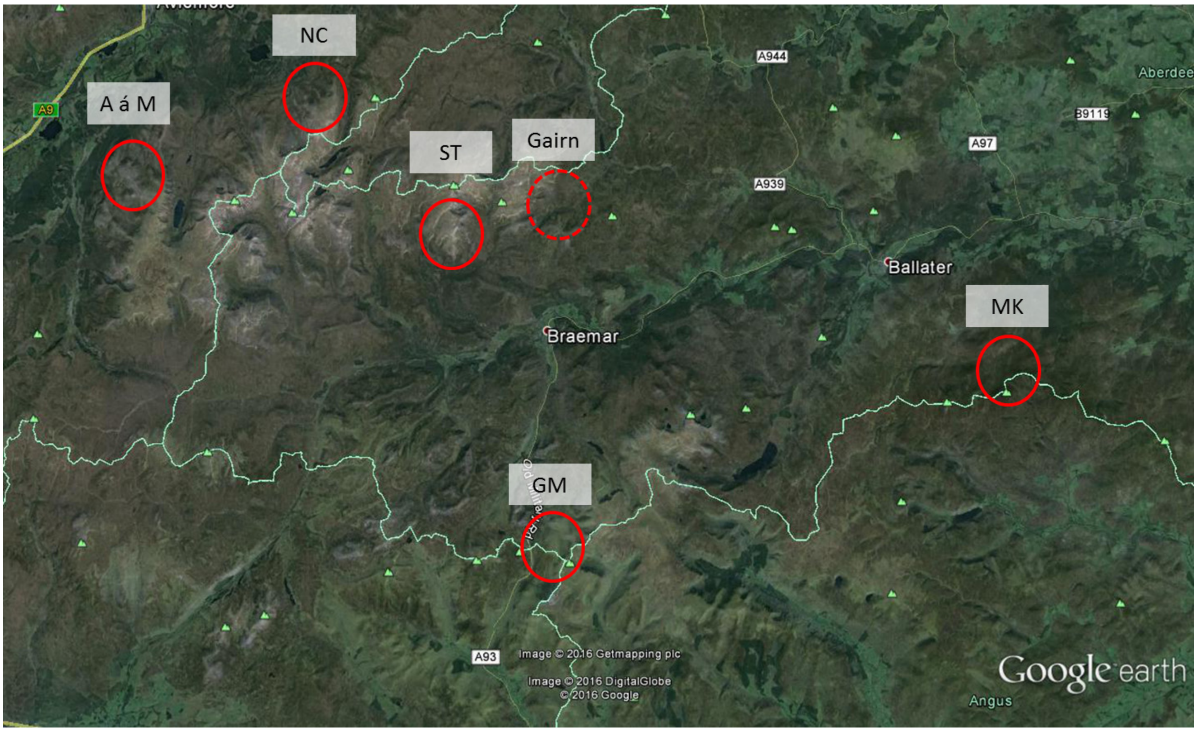

Figure 2. Satellite image of central Cairngorms area. The five sites included in the field survey are indicated by red circles (solid line): Allt á Mharcaidh (A á M), Glas Maol (GM), Mount Keen (MK), Northern Corries of Cairngorm (NC), South Top of Beinn á Bhuird (ST). Also shown is the location of the Gairn catchment where the main translocation experiment was conducted (Gairn). Satellite image copyright Google Earth.

A semi-randomised survey was undertaken at each site. A problem with surveying a patchily-distributed species such as *F. nivalis* is that randomly placed quadrats in many cases do not contain the species of interest. In order to overcome this and improve the quality of the data for modelling, our surveying design increased sampling effort in areas when *F. nivalis* was detected. This ensured a better balance within the dataset of data from quadrats with and without the lichen.

Within each site we selected slopes where we expected to find *F. nivalis* based on prior knowledge of the lichen's distribution. At regular distances on each slope, transects were placed along altitudinal contours. Transect starting points were selected beforehand. Elevation range of transects is shown in Annex 1. The vegetation encountered ranged from 50 - 60 cm tall *Calluna* heath at the lowest altitudes, to fellfield vegetation with patches of *Racomitrium lanuginosum* at the highest altitude.

At least five plots were placed along each transect, (min. 50 m between plots). When a plot location was reached, if the location conformed to habitats known to be unsuitable for *F.*

nivalis (e.g. snowbed or *Sphagnum*-dominated vegetation) the plot was established in the next area of suitable vegetation. At the plot location a plastic pole was driven into the ground and a 10 m circle demarcated. If *F. nivalis* was detected within this circle, the plot was re-centred on the *F. nivalis* closest to the pole. This increased the chance that recorded data captured at the circle level (and also quadrat level – see below) included the key factors regulating lichen occurrence

Within the 10 m circle we recorded slope (using a clinometer), aspect (from a compass reading), dung (occurrence of sheep, hare, grouse or deer dung), plot-level topography (convex, concave or flat). A 1 m x 1 m quadrat was then centred on the pole. Within this we recorded vegetation cover, as well as cover of bare ground (stones, rocks/gravel, peat), dung and litter (dead plant material). We also recorded sward height (four points, one centred in each quarter of the quadrat). If *F. nivalis* was present, four extra quadrats were surveyed, one adjacent to each side of the initial central quadrat. The same quadrat-level measurements were undertaken within each of these four new quadrats, although plot-level measurements (at the scale of the 10 m circle) were not repeated.

2.1.2 Development of the training model

From the survey data we developed the training model, assessing the parameters that best predicted the natural occurrence of *F. nivalis* within the survey sites. The training model was a Generalised Additive Mixed Model (GAMM) with autocorrelated errors. Factors introduced into the model included data from the vegetation survey and a number of derived variables.

First, minimum and maximum monthly temperatures were derived using plot coordinates from a previously-produced interpolated climate surface for the region of interest (Poggio & Gimona, 2015).

Second, to reduce the number of vegetation parameters included in the model, vegetation percentage cover data were simplified through a cluster analysis, which aimed at identifying a smaller number of vegetation types across the survey dataset. We clustered quadrat species abundance data using the Bray-Curtis and Ward methods (Bray & Curtis 1957; Kaufman & Rousseeuw 1990) to build a clustering dendrogram. We then cut the dendrogram based on our judgement that the groups (clusters) occurring at that level within the dendrogram represented distinct and genuine vegetation types. Seven vegetation groups were derived based on this approach.

Initial modelling indicated that variation in vegetation height, occurring between vegetation groups, was a major factor in structuring the groups. We tested this conjecture by including vegetation height in the training model; vegetation height explained the same amount of model deviance as vegetation groups. The potential for replacing vegetation group with height is probably enhanced by our active exclusion from the vegetation survey of locations with clearly unsuitable vegetation (e.g. *Sphagnum*-dominated or late snowbed vegetation), such that for a given vegetation height there is restricted variation in vegetation type. Because vegetation height is much easier to calculate for locations not included in the initial survey (e.g. for the recipient sites at Invercauld) we substituted vegetation height for vegetation group within the final training model.

2.2 Translocation trials and application of model to transplants

2.2.1 Establishment and monitoring of main transplant experiment

The main trial translocation of *F. nivalis* was established on the Invercauld Estate, specifically in the upper Gairn catchment (Figure 2). This site was chosen because it sits within the natural range of *F. nivalis*, and the area's vegetation and topography is very varied (thus enabling a robust test of the model). In addition, substantial populations of *F. nivalis* occur close to the site, and these were used as source material for transplants, allowing us to test our model without the potentially confounding effect of moving the transplants a long distance.

In September 2010, *F. nivalis* thalli were collected from the Culardoch and Carn Liath donor sites (just outside the southern boundary of the recipient site). Large thalli were collected; these were subdivided to provide multiple individuals for transplanting. For collection, thalli were moistened with demineralised water, and when pliable placed in plastic bags and kept cool during transport to the laboratory. In the laboratory, very large thalli were subdivided in order to provide sufficient individuals for transplanting. Each resulting thallus – hereafter 'transplant' – was approximately 3 to 4 cm in length and width. Each transplant was washed in demineralised water to remove adhering debris (with extra cleaning when necessary) and left to dry at room temperature for two days, after which it was weighed. The transplant was then rehydrated, a red cotton thread was tied around one part of the transplant to help with relocation in the field, and a short piece of thin plastic-coated wire securely looped around the middle of the transplant to enable it to be firmly pinned down to the ground. A treated thallus can be seen in Figure 3.

As well as survival and mass change, we attempted to measure thallus growth, employing a technique previously utilised for measuring lichen growth in coastal dune systems (Rebecca Yahr (Royal Botanic Garden Edinburgh) personal communication); this involved attaching a small entomology pin to the thallus using silicon, the pin being set at 5 mm from the thallus edge.

Figure 3. The left hand image shows a Flavocetraria nivalis *transplant following placement in the field. The image also shows the green plastic coated wire used for attaching the lichen to the ground, as well as the short piece of red cotton thread, attached to the thallus to aid with re-location. The right-hand picture shows the top of one of the small shelters placed around some of the transplanted lichens; the lichen is inside the shelter, covered with snow.*

Prepared transplants were placed out at the Invercauld site on 20-22 September 2010. Locations for recipient plots were selected beforehand based on a NVC vegetation map of the catchment, and to give a range of altitudes, vegetation types, and aspects. This meant that some lichens were translocated into habitat that we considered to be unsuitable (the 'boundary' habitats for *F. nivalis*), but this helped to provide a robust test of the model.

Four transplants were placed out at each recipient plot. These marked the corner of a 1 m x 1 m square with its sides orientated towards the cardinal points. Lichens were attached to the ground using a small metal pin fed through the length of wire looped around the transplant. The four transplants were randomly allocated one to each of four treatments: control, neighbour removal (clipping neighbouring vegetation to ground level within 20 cm of the transplant), shelter (a 10 cm diameter x 10 cm tall plastic cylinder made of 2 cm garden mesh covered with netlon – see Figure 3), and clipping + shelter. The additional treatments were to assess whether active management enhanced survival.

Plots were revisited 28 July to 3 August 2011. When revisiting a plot, if a thallus was missing we checked in the immediate vicinity in case it had detached from the wire but re-attached to surrounding vegetation; when this was the case we recorded it as present. During these checks we noted that the small entomology pins had detached from many transplants, and so we decided to trial a new method for measuring thallus growth. All transplants were transported back into the laboratory and an assessment of first year survival was made based on presence (absence was assumed to equate to mortality) and a health score based on signs of decomposition and necrosis (brown and black discolouring and fragmentation of the thallus). For all locations where a transplant 'survived' from 2010 to 2011 we prepared a new transplant in an identical manner, but with a red cotton thread sewn through the thallus at a recorded point back from the thallus edge. Importantly, we did not place fresh transplants at all locations used in 2010 but, in order to minimise the number of thalli taken from the donor population, only where the lichen had been assessed as surviving. The new transplants were placed out between 19 and 22 September 2011 and monitored annually until 2015.

Additional measurements were also made at the recipient plots. Vegetation was recorded within the 1 m x 1 m square in an identical manner to the wider vegetation survey. In addition a vacuum-packed DS1921G Thermocron iButton temperature logger (Maxim Integrated Products, CA, USA) was buried just below the soil surface in the centre of each plot. iButtons were programmed to record temperatures at 2-hourly intervals from 30th August 2011 until collection in September 2012.

All surviving lichens were collected on 24 to 28 August 2015, and taken to the James Hutton Institute, Aberdeen, where they were cleaned, initially by washing in water and then through careful removal of any material still adhering to the thallus. They were then left to air dry before being weighed. Original (2011) mass was subtracted from final (2015) mass to assess absolute thallus mass change from 2011 to 2015.

2.2.2 Take and replace trials

An issue with conservation translocations is the potential for mortality to be caused by the translocation process itself (Brooker *et al.*, 2011). In assessing the efficacy of any transplantation technique this must be taken into account. To assess this we undertook a simple take and replace trial. The aim was to take lichens from the donor population, treat them as for the main transplant experiment, and then to return them to their original locations. As we know that the original locations are suitable for the lichen, we can then infer that any mortality was due to the translocation process.

More details of this trial are provided in Annex 2. In summary, survival of transplants was very high (approaching 100%) and so we can conclude that mortality of translocated lichens is not due to the translocation process. In addition change in thallus mass showed a similar pattern to survival, indicating that the processes governing thallus mass change and survival are similar.

2.2.3 Data analysis

The training model from the vegetation survey was refitted to first year transplant survival data (i.e. records of survival taken in 2011, following one year in the field for the transplanted lichens). The training model was refitted as a Generalised Additive Model (GAM) using the original significant terms, specifically minimum February and July temperature, aspect, altitude, and vegetation height. We also included the clipping and shelter treatments and their interaction as fixed effects within this model.

The training model had very low predictive power for first year (2010-2011) survival of transplants (see Section 3.2). To help improve model fit we included summary temperature data derived from the iButton, specifically average monthly temperature values from September 2011-August 2012. Although these records do not come from the same year as the initial survival data, they do provide us with an indication of relative variations in small-scale microclimatic conditions between the plots within the recipient site. The revised model was applied to 2011 and 2015 records of lichen survival. Models were refined through a number of steps. First, except for the shelter and neighbour removal treatment variables (as we specifically wanted to test their effect), non-significant variables were excluded. Then, factors which were initially fitted as smooth terms, but which showed linear relationships with survival, were refitted with linear relationships. For those models where summary iButton data were included, the climate parameters derived from interpolated climate surfaces were excluded.

The revised model was applied to 2011 and 2015 records of lichen survival, as well as to 2011-2015 thallus mass change data. Because fewer lichens were monitored for mass change during the period 2011-2015 (i.e. only those lichens replaced during 2011), it was necessary to reduce the number of variables included in the model. In particular we used only average iButton temperature data from September and February; tests with various combinations of temperature data indicated that changing temperature data combinations had minimal impact on the results.

2.3 Out of range trials

The Invercauld recipient site sits within the current range of *F. nivalis* (Figure 1). An additional challenge for the training model is to predict survival of the lichen outside its present range. We tested application of the training model outside of the current Scottish range of *F. nivalis* by using it to select recipient sites at the Creag Meagaidh SSSI. We then transplanted *F. nivalis* into these sites and monitored their success. Creag Meagaidh was chosen as a test site because it is close to the edge of the current distribution of *F. nivalis* in Scotland and has similar vegetation to that of the main Cairngorm plateau. The translocation was conducted following the Scottish Code for Conservation Translocations and best practice guidelines (National Species Reintroduction Forum, 2014a,b) and a licence obtained after completion of a ‘Translocation Project Form’ (as outlined in the guidelines).

2.3.1 Selection of recipient sites at Creag Meagaidh using the training model

In order to select recipient sites we applied the training model (as described in section 2.1.2) to data from the Creag Meagaidh site. We did not have vegetation height data for the Creag Meagaidh site, but did have maps of NVC classifications. Consequently we included vegetation data in the model rather than vegetation height. We used expert judgement to link NVC classes found at the site to the seven vegetation groups identified by the cluster analysis. We then used the training model to map probability of occurrence of the lichen at Creag Meagaidh. Probability of occurrence was used as a proxy for habitat suitability.

The results of the mapping exercise are shown in Figure 4. We positioned the trial plots at the Eastern end of the Creag Meagaidh SSSI, more specifically on the northern side of the ridge running to the west from the summit of Carn Liath (NN472903 - not to be confused with the hill of the same name on the southern edge of the Invercauld site). This site was chosen because it is not on the main high-level walking circuit for Creag Meagaidh, and it also contains patches of habitat that the training model predicted to be both good and bad for *F. nivalis*. Within this area we selected locations that represented a range of predicted suitability (probabilities of occurrence).

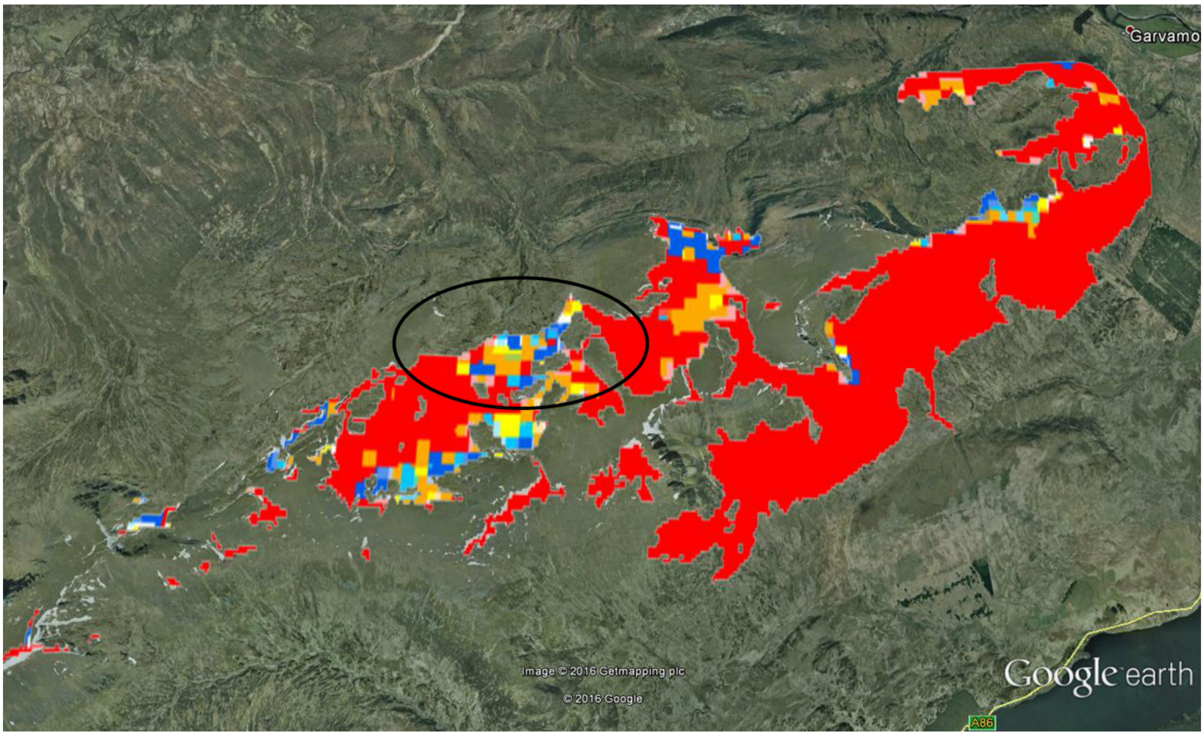

Figure 4. Satellite image of the eastern end of the Creag Meagaidh SSSI (Loch Laggan shown in the bottom right-hand corner) with the results of application of the training model superimposed onto the terrain surface. Grid cells are approx. 100 m x 100 m. Predicted probability of occurrence: red = 0–0.2; orange = >0.2–0.4; yellow = >0.4-0.6; pale blue = >0.6–0.8; dark blue = >0.8–1. The recipient sites were located within the circled area. Satellite image copyright Google Earth.

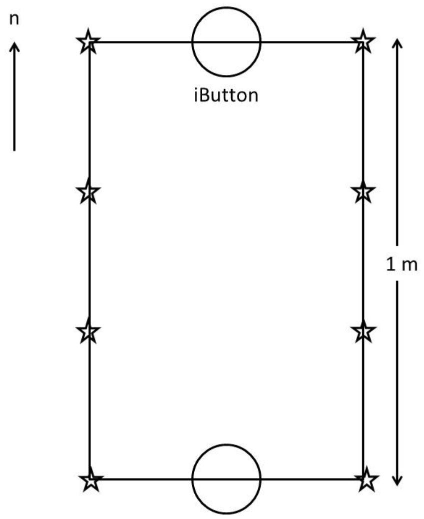

Figure 5. Arrangement of lichens within out of range trial plots. Plots were 1 m long and 0.5 m wide, with the long axis orientated south-north. Eight lichens – indicated by star symbols - were placed out at each plot. To aid with plot relocation two small plastic shelters, as used for the shelter treatment in the main transplant trials, were placed out, one at either end of each plot (circles). The position of iButton within the plot is also shown.

2.3.2 Establishment and monitoring of out of range transplants

The out of range trial plots were established in September 2012. Beforehand, we collected *F. nivalis* thalli from the Culardoch and Carn Liath donor sites and treated them in the same way as the thalli used in the main transplant experiment at the Invercauld site.

The plots were established along a transect running in a roughly south-west to north-east direction across the northern slope of Carn Liath. Plots were roughly equally spaced, although their exact location depended on the position chosen from the modelling process. Ten plots were placed out along this transect.

To establish a plot, we used a GPS to locate the position indicated as the centre of the relevant pixel on the Google Earth surface (Figure 4). We then positioned the plot as close to this point as possible, avoiding only clearly unsuitable habitat. Within each plot, eight lichens were placed out using the same procedure as for the main transplant trial, and arranged in the pattern shown in Figure 5.

Lichens were monitored at the site until September 2015, using the approach applied in the main transplant experiment. In addition iButtons were placed in each plot from 3 September 2014 to 1 September 2015.

Just prior to harvest we also recorded vegetation and other plot-scale data using the methodology applied in the field survey, as well as recording vegetation cover data within small (20 x 20 cm) quadrats focused on each lichen. Lichens were harvested on 1 and 2 September 2015 and treated in a similar manner to those from the main transplant experiment.

2.3.3 Data analysis

We were not able to re-apply to the Creag Meagaidh data the full modelling approach as used previously at the Invercauld site. This is because there were only 10 plots at the Creag Meagaidh site, with limited variation between plots in terms of altitude, aspect and temperature (based on preliminary analysis of iButton data). In addition, at the time of harvest one of these plots could not be relocated, further reducing available replication.

Consequently we adopted a simpler approach to data analysis. Our main aim was to test whether the training model was able to predict the success of lichens at the Creag Meagaidh site. To assess this we undertook simple linear regressions of lichen survival against predicted plot quality. To further explore variation in lichen success, we also undertook regression of lichen survival against a number of key variables that we believed might influence success at this site; in particular sward height, the cover of *Sphagnum* (as an indicator of wetter ground), and the cover of *Vaccinium* species (as an indicator of drier ground).

3. RESULTS

3.1 *Flavocetraria nivalis* field survey

The training model had some predictive power when applied to the data from the vegetation survey; 27.2% of the deviance within the data was explained. The significant parameters within the final model were the minimum temperatures in February (P<0.05) and July (P<0.05), aspect (P<0.001), and altitude (P<0.01), with vegetation height being marginally significant (P<0.065). Altitude was positively related to lichen occurrence, and vegetation height negatively related, indicating that lichens occur at high altitude sites with short stature vegetation.

3.2 Experimental transplants

3.2.1 Transplant survival

Despite the reasonable fit and simplicity of the training model, when applied to first year (2010-2011) survival data the model performed poorly (Table 1). Only altitude and vegetation height had significant effects on lichen survival. The effect of altitude was complex, with slight evidence of peak survival at approx. 800 m, with survival then broadly declining beyond this point. The increase in survival up to 800 m may be due to reductions in vegetation height, which itself had a negative relationship with survival. Above 800 m the plots become more exposed (high altitude ridges) and survival decreases.

Table 1. Results from modelling of transplant survival at the recipient site. Columns indicate factors included within the models and the significance (= P<0.05, ** = P<0.01, ***=P<0.001, † = P<0.10, "ns" = non-significant) of their effect on survival recorded in 2011 and 2015. Only factors with a significant effect within at least one of the models are shown. "T Average" indicates the temperature average, as assessed from iButton data, for that month. "N.A." indicates that the factor was not included in that model. Column headings also indicate which climate data were included in the model – data from interpolated climate surfaces or iButton microclimate data. The bottom row indicates the percentage of total deviance of the data explained by the model (i.e. quality of model fit).*

	2010-2011 interpolated	2010 – 2011 iButton	2010-2015 interpolated	2010-2015 iButton
Altitude	0.008**	ns	0.044*	ns
Vegetation height	0.005 *	ns	ns	<0.001***
Slope	ns	ns	0.079†	ns
T Average 01/12	N.A.	ns	N.A.	0.002**
T Average 04/12	N.A.	0.047*	N.A.	ns
T Average 05/12	N.A.	<0.001***	N.A.	ns
T Average 06/12	N.A.	ns	N.A.	<0.001***
T Average 07/12	N.A.	ns	N.A.	0.004**
% of total deviance explained	10.7%	8.5%	9.5%	25.3%

Inclusion of microclimatic data from the iButtons did not improve model fit for 2011 survival data, with model fit being slightly reduced. However, the replacement of vegetation height and altitude with the variables derived from the iButtons indicates that the climate data extracted from interpolated climate surfaces were inadequate in representing the climatic variability experienced by the transplants, or at least that the variance associated with these data was already adequately captured by other parameters such as altitude and vegetation height. The responses of lichen survival to the iButton data were not straightforward. There was a negative relationship between survival and December average temperatures. This seems logical: survival is highest in more exposed sites (with shorter vegetation) where winter temperatures are lower. But the relationship to May temperatures was positive, indicating that survival is greater in warmer sites. This second relationship is more difficult to explain, but may be related to temperature inversions during stable weather patterns in the spring, with cold air flowing from high to low ground overnight such that more exposed sites are warmer.

Response patterns for 2015 survival data differed from those for 2011 survival data. In the absence of iButton data the model fit was still weak (9.5%). Altitude continued to have a significant effect on survival, with a similar pattern to that shown for 2011 survival. With the addition of iButton data, the model fit for 2015 survival was very substantially improved (25.3%). Vegetation height was now a very significant factor, with increasing vegetation height having a negative impact on survival. However, altitude was no longer a significant explanatory variable. As for the model of 2011 survival which included iButton data, the iButton-derived parameters may capture the variance associated with altitude and slope. Once again, the relationship of the iButton parameters to survival was not straightforward. June and July temperatures showed a broadly positive and negative relationship respectively to survival, whereas the relationship with January temperatures was more complex.

3.2.2 Transplant 2011-2015 thallus mass change

The only factor identified as significantly influencing thallus mass change between 2011 and 2015 was average 2011 September temperature as derived from iButton data (T Average 9/11, P=0.0455); there was a weakly positive relationship between thallus mass change and average September temperature. Overall the model explained 3.13% of the deviance in the thallus mass change data, and so was very poor at explaining variation in recorded mass change.

3.3 Out of range trials

Linear regressions of plot-level data indicated no significant effect of predicted plot suitability on lichen survival, or any effect on survival of sward height or the cover of *Vaccinium* species (P>0.4 in all cases).

We also explored the impact of vegetation parameters at the level of the 20 x 20 cm quadrats focused on individual lichens. As lichens are nested within plots, this analysis was undertaken using a Generalised Additive Model (GAM) with a logit link function to account for the binomial nature of the data; factors included in the model were the cover of *Sphagnum*, the cover of other mosses, and the cover of *Vaccinium* species. This model demonstrated a significant negative impact of *Sphagnum* cover (P < 0.01) and a borderline significant positive effect of *Vaccinium* species cover (P=0.056); the model explained 20.4% of data deviance.

4. DISCUSSION

Following our initial literature review (Brooker *et al.*, 2011) we selected two key research questions to address through field trials. By combining the results from our survey of the distribution of *F. nivalis* and the development of an associated training model, and the trial translocations at the Invercauld and Creag Meagaidh sites where the training model was applied, we can answer these two questions.

Question 1 - Is it possible to develop a model to predict the location of suitable habitat for the translocated species, and does this model include climate parameters as key factors regulating the species' distribution?

The field survey enabled us to develop a model for the occurrence of *Flavocetraria nivalis*, interpreting occurrence as indicating habitat suitability. Climate parameters were indeed included within the model as significant variables, an essential if the model is to be used to forward-project the location of suitable environmental space under a future climate scenario. However, the model had low explanatory power, both for the natural distribution of the species and for the survival and growth of transplants, and this is likely to be due at least in part to the strong influence of small-scale variation in micro-climatic conditions. Other factors may include gaps in the current range of *F. nivalis* such that its realised distribution does not fully match its potential distribution.

Question 2 – Is it possible to apply this model to detect suitable habitat for a species outside its current Scottish distribution?

Perhaps not surprisingly given low predictive power even within the target species' range, we could not apply this model to detect suitable habitat for this species outside of its current range.

Considering our results in more detail, the training model developed from the vegetation survey data indicates the strong impact of abiotic parameters (aspect and altitude) on the natural distribution of *F. nivalis*, as does the substitution of vegetation group by vegetation height during training model development. The apparent strong impact of abiotic parameters on *F. nivalis'* distribution matches well with our existing knowledge of the autecology of terricolous mountain lichens (Crabtree & Ellis, 2010).

Notably, there remains a large amount of unexplained variation within the training model. This may result from a number of factors operating across scales. First, at a very large scale, stochastic and biogeographic factors (e.g. dispersal limitation) may have impacts on species distributions, preventing a species from filling the available suitable climate space (Lortie *et al.*, 2004). In practice this could mean that the realised distribution of *F. nivalis* does not match perfectly the distribution of suitable habitat, an effect that is difficult to account for within model development.

Second, environmental data included within the training model may not accurately reflect the conditions experienced by the lichens. For example, when the training model is applied to transplant survival at Invercauld (Table 1), climate variables based on the interpolated climate surfaces are excluded from the model (2011 survival data) indicating they have weak explanatory power. In contrast, inclusion of climate variables based on iButton data greatly improves model fit for 2015 survival data (Table 1). This indicates that the data from interpolated climate surfaces do not reflect accurately the climatic conditions experienced by the lichen, leading to unexplained variance in the training model. Small-scale variability in environmental conditions has been recognised previously as potentially critical for species such as *F. nivalis* that sit within microclimatic pockets within the surrounding vegetation, being decoupled from the environmental conditions immediately above the vegetation surface or modelled at a coarser spatial resolution (Pradervand *et al.*, 2014). However, in both this and previous studies (e.g. McLane & Aitken, 2012), improvements in model fit can be achieved through the deployment of relatively simple technology such as iButton temperature loggers to provide an indication of finer-scale climatic conditions.

The management treatments did not have significant impacts on *F. nivalis* survival in any of the models examined. This is surprising given that we might have expected them to influence the micro-climate. However, a small-scale environmental effect is demonstrated by the results from the Creag Meagaidh out of range trial, where lichen survival was negatively associated with the cover of *Sphagnum*. Notably this effect was stronger for analyses at the individual lichen level than at the plot level, indicating that the vegetation immediately beneath the lichen is critical for determining success, and that plot level records of vegetation composition may not be capturing the critical features of the vegetation as experienced by the lichen. *Flavocetraria nivalis* is sensitive to prolonged snow cover or high moisture levels, as indicated by its absence from areas of relatively late-lying snowbed (e.g. *Nardus stricta* dominated snowbed communities) or from vegetation with a *Sphagnum*-dominated ground layer (Gilbert & Fox 1985). It may be that the damper conditions occurring above *Sphagnum* had a negative impact on transplant survival.

However, even with the inclusion of iButton data, the training model fit when applied to 2011 survival data at the Invercauld experimental site (Table 1) was weaker than for the wider vegetation survey. The improvement in model fit from 2011 to 2015 indicates that poor model fit in 2011 is likely to be created in part by a lag in the response of transplants to their new location. Specifically, lichens may take a long time to die. Hence in 2011 lichens may still be persisting in sites that are unsuitable for them; by 2015 many of these lichens have died, such that the distribution of the surviving transplants more accurately reflects the distribution of suitable environmental conditions for *F. nivalis*.

The differing results for mass gain and survival indicate that, for this species, the long-term pattern of survival does not reflect a long-term pattern of growth. Although this may mean that growth and survival are to some extent decoupled, it may also simply be a consequence of the difficulties of accurately measuring growth in lichens.

The apparently slow mortality of lichens emphasises the need for long-term monitoring when assessing the success of translocations. The need for – and frequent absence of – long-term monitoring in conservation translocations has been noted previously (see Brooker *et al.*, 2011 and references therein) and our experimental work suggests this is particularly true for species that are relatively slow to respond such as alpine lichens.

As well as testing the training model at the Invercauld site, we also trialled the model at Creag Meagaidh, a site outside of the current range of *F. nivalis*. Because of the lower level of replication at this site we were unable to fit the full training model to Creag Meagaidh data. However, we were able to examine whether the quality of the plots – as predicted by the training model – was related to lichen survival. We detected no strong relationship with predicted plot quality. This is likely to result from applying a model with low predictive power even within the natural range of the target species, to an area outside of the species' range and where we have only proxies for some of the key parameters (e.g. using NVC records as a substitute for vegetation type). However, and as noted above, we did find a strong relationship with *Sphagnum* cover, demonstrating once again the strong impact on success of very localised environmental conditions.

5. CONCLUSIONS AND RECOMMENDATIONS

This project has tested some of the key assumptions behind the concept of conservation translocations as an adaptation strategy for species conservation during climate change. It has also resulted in substantial knowledge exchange activity (Annex 3) demonstrating the current interest in this topic. A number of conclusions and associated recommendations can be drawn from this work that are of direct relevance to guiding future translocations of similar species.

Conclusions

- As indicated by our take and replace trials, it is possible to successfully translocate foliose terricolous alpine lichens such as *Flavocetraria nivalis*. The techniques applied here might be applied to translocate and monitor other threatened lichen species in a range of environments.

- For slow-growing species such as alpine lichens, it may take a long time for the success (or otherwise) of conservation translocations to become clear.

- For small stature species it is difficult to develop a model that accurately predicts the precise location of environmental conditions suitable for their survival and establishment, not least because of the strong influence of small-scale microclimatic and vegetation effects. This may be particularly true for immobile species – for example many bryophytes and lichens - which are unable to adjust their location following transplantation. It may also be particularly true for species whose survival and growth is strongly affected by abiotic environmental conditions (for example arctic or alpine species).

Recommendations

- When translocating immobile species that are likely to be strongly affected by the abiotic environment and small-scale variation in environmental conditions, a combination of modelling (based on distribution data) and expert judgement is likely to be an effective way of selecting recipient sites. Within a broader area selected through modelling, expert judgement will allow localised tailoring of the final exact location of a transplant to best suit the species' requirements.

- Successful translocations of this type of species might also necessitate the movement of a large number of transplants. This would help to overcome the problem of high initial mortality due to the strong influence of localised environmental conditions on initial survival. However, this also has implications for selecting the threshold population size at which a positive decision to translocate is made: this will have to be much higher if there is going to be considerable post-translocation mortality.

- Overall, and at least when dealing with this type of species (small, immobile, and highly responsive to local environmental conditions), it is very unlikely that we can develop accurate forward projections of the future spatial location of suitable habitat and environmental conditions. A pragmatic and flexible approach to their conservation under climate change may be needed, including establishing new populations at a range of locations, and repeating translocations through time.

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ANNEX 1: SUMMARY DATA FOR SITES INCLUDED WITHIN THE FIELD SURVEY

Summary data for sites included within the wider field survey. The table shows the dates on which the sites were surveyed, the range of altitudes covered by plots within the sites and their mean aspect, the total number of plots and 1 m x 1 m quadrats surveyed (>1 quadrat is placed at a plot if *F. nivalis* is present), and the total number of 1 m x 1m quadrats that contained *F. nivalis*.

Site	Allt á Mharcaidh	Glas Maol	Mount Keen	Northern Corries, Cairngorm	South Top, Beinn á Bhuird
Dates surveyed	10/8/10 – 31/8/10	23/8/10 – 25/8/10	27/6/11 – 28/6/11	9/8/10 – 10/8/10	26/7/10 – 27/7/10
Altitudinal range (m)	564-1103	647-1051	500 – 900	559-1199	596-1182
Mean aspect (± standard error)	199.1 (13.0)	189.8 (11.1)	192.8 (19)	218.9 (17.0)	161.4 (19.2)
No. of plots surveyed	66	53	49	62	65
No. of 1 m x 1 m quadrats surveyed	138	65	49	134	141
No. of 1 m x 1 m quadrats with lichen	43	4	0	28	40

ANNEX 2: TAKE AND REPLACE TRIAL METHODOLOGY AND RESULTS

Methodology

The take and replace trials were established near the summit of Carn Liath (Invercauld) on the southern edge of the main transplant trial recipient site, in the area previously used as a donor population for the main transplant experiment and out of range trials.

Within this area seven transects running west to east, and varying in length from approximately 5 to 8 m were established. Transect ends were permanently marked using metal pegs; the locations of transect ends were also recorded using a hand-held GPS device (Garmin eTrex Vista HCx). Four clumps of *Flavocetraria nivalis* were identified near to each transect. Their locations relative to the transect were recorded, and they were photographed so that they could be relocated.

On 20 June 2014 two thalli were extracted from each lichen clump, and treated as for the main transplant trial. They were then returned to their source location on 29th June 2014, one transplant being placed in the centre of the source clump, and the other on the edge of the clump (ideally on the eastern side of the clump, although given the stony nature of the ground this was not always possible).

The transplants were then revisited on 8th September 2015 at which point survival was again recorded. Transplants were collected and returned to the laboratory for processing as for the main transplant trial.

Results

One transect had been destroyed by heather burning during the monitoring period. For data analysis, transect level values for survival and thallus mass change were combined to give average values at the transect level.

Within the six remaining transects, survival was 100% in the centre of clumps, and 95.8% on the edge of the clumps. Average mass change was 0.014 g in the centre of clumps (standard error = 0.011 g), and 0.025 g on the edge of the clumps (standard error = 0.0068). Survival and mass change did not differ significantly between clump centres and edges ($P>0.05$ for both survival and mass change; 2-sample t-test).

Overall, therefore, survival levels were high during the take and replace trial. Admittedly we were only able to run this trial for a single year, and long-term monitoring is needed for species that are slow to respond and which can take a long time to die. However, our experience with *F. nivalis* transplants suggests it is possible to spot the early signs of mortality within this species, including discolouration and necrosis. For the take and replace trial lichens such signs were extremely rare, making us relatively confident that high short-term survival would have translated also into high long-term survival.

ANNEX 3: LIST OF KNOWLEDGE EXCHANGE ACTIVITIES AND OUTPUTS DELIVERED BY THIS PROJECT

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