



Are existing biodiversity conservation strategies appropriate in a changing climate?

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Oliver, T. H., Smithers, R. J., Beale, C. M. and Watts, K. (2016) Are existing biodiversity conservation strategies appropriate in a changing climate? *Biological Conservation*, 193. pp. 17-26. ISSN 0006-3207 doi: <https://doi.org/10.1016/j.biocon.2015.10.024> Available at <http://centaur.reading.ac.uk/57278/>

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To link to this article DOI: <http://dx.doi.org/10.1016/j.biocon.2015.10.024>

Publisher: Elsevier

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Are existing biodiversity conservation strategies appropriate in a changing climate?

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Highlights

- Using the UK as an example, we apply a climate change adaptation decision framework
- Thirty threatened species were assessed across three broad habitat types
- We compared adaptation actions with government conservation recommendations
- There were large differences in the spatial prioritisation of recommended actions
- Conservation plans failing to take account of climate change may fail to maximise species persistence

Abstract

Many countries have conservation plans for threatened species, but such plans have generally been developed without taking into account the potential impacts of climate change. Here, we apply a decision framework, specifically developed to identify and prioritise climate change adaptation actions and demonstrate its use for 30 species threatened in the UK. Our aim is to assess whether government conservation recommendations remain appropriate under a changing climate. The species, associated with three different habitats (lowland heath, broadleaved woodland and calcareous grassland), were selected from a range of taxonomic groups (primarily moths and vascular plants, but also including bees, bryophytes, carabid beetles and spiders). We compare the actions identified for these threatened species by the decision framework with those included in existing conservation plans, as developed by the UK Government's statutory adviser on nature conservation. We find that many existing conservation recommendations are also identified by the decision framework. However, there are large differences in the spatial prioritisation of actions when explicitly considering projected climate change impacts. This includes recommendations for actions to be carried out in areas where species do not currently occur, in order to allow them to track movement of suitable conditions for their survival. Uncertainties in climate change projections are not a reason to ignore them. Our results suggest that existing conservation plans, which do not take into account potential changes in suitable climatic conditions for species, may fail to maximise species persistence. Comparisons across species also suggest a more habitat-focused approach could be adopted to enable climate change adaptation for multiple species.

Key words

Habitat management and restoration, connectivity, threatened species, vulnerability, adaptive capacity, translocation

1. Introduction

Climate change is already impacting upon biodiversity and represents an important future challenge for biodiversity conservation strategies (Bellard *et al.* 2012). Interactions between climate and land use provide opportunities for climate change adaptation that increase species' adaptive capacity (Smithers *et al.* 2008; Heller & Zavaleta 2009; Oliver & Morecroft 2014). In many cases, existing conservation policy and practice already promote actions that will reduce vulnerability to climate change (e.g. habitat management, restoration or creation that improves the functional connectivity of landscapes). However, explicitly addressing climate change impacts when developing species and habitat action plans could lead to differences in the balance of recommended conservation actions or in the priority given to actions in different locations. At present, we do not know the extent of these differences and their likely importance, yet such information will be critical in designing biodiversity conservation strategies that will remain appropriate and effective under climate changes in coming decades.

In this study, we use the UK as an example and demonstrate the use of a climate change adaptation decision framework to consider the efficacy of national government conservation recommendations for threatened species. In the UK (which comprises Great Britain and N. Ireland), threatened species are identified in the Natural Environment and Rural Communities Act 2006 (NERC Act). Conservation plans have been identified for many of these species and are documented on the website of the statutory body responsible for co-ordinating conservation in the UK (Joint Nature Conservation Committee, JNCC; <http://jncc.defra.gov.uk>). These plans have been developed by JNCC with input from species experts and list key actions that are thought necessary to protect and enhance the status of the threatened species. However, they do not explicitly consider the projected impacts of climate change scenarios, which may vary in magnitude and direction of effect across species ranges (Berry *et al.* 2002; Pearson & Dawson 2003). Climate change has the potential to compound other drivers of population decline (Brook *et al.* 2008; Oliver & Morecroft 2014). Threatened species may be particularly vulnerable, as a consequence of their small populations, limited geographic ranges or both (IUCN 2001).

A climate change adaptation decision framework was recently published (Oliver *et al.* 2012; Oliver *et al.* 2015), aiming to promote integration of climate change adaptation principles into conservation planning by prioritising and targeting relevant actions to increase the adaptive capacity of species (Hopkins *et al.* 2007; Huntley 2007; Mitchell *et al.* 2007; Smithers *et al.* 2008; Heller & Zavaleta 2009; Mawdsley *et al.* 2009; Pettorelli 2012). In doing so, the framework extends the prioritisation of landscape-scale actions by Lawton *et al.* (2010) from 'more, bigger, better, joined' to 'better, bigger, more, improve connectivity, translocate and ex-situ'. Thus, it reflects recent debate about the need to address existing threats to species before enhancing functional connectivity (Hodgson *et al.* 2011). The decision framework helps users to prioritise adaptation actions for species through qualitative consideration of results from climate envelope / species distribution models (hereafter referred to as 'bioclimate' models; Pearson & Dawson 2003; Elith & Leathwick 2009). The framework also uses available data on species attributes and status (e.g. frequency of occurrence, population trends, habitat associations and dispersal abilities), habitats (e.g. quality, extent and fragmentation) and land cover (with regard to potential edge effects from land use surrounding habitat patches and the permeability of the intervening matrix).

In the current study, we assessed 30 NERC Act species using the decision framework. The aim of our study was to compare how existing conservation actions identified nationally for these species differ from those keyed out using the decision framework.

2. Methods

2.1 Species selection

From the NERC Act 2006 priority species list, an initial long-list of 114 species was identified for which the UK Biological Records Centre (BRC) held sufficient data to calculate a trend over time in frequency of species' occurrence (see Section 2.4). Our subsequent intent was to select 30 of these species associated with three different habitat types: lowland heath, broadleaved woodland or calcareous grassland. These habitats were chosen, as they are widespread in the UK, can be mapped using remote-sensing data, and host a large number of other species of conservation concern. Species-habitat associations were determined from Webb *et al.* (2010). We randomly selected ten species associated with each habitat type and across a range of taxonomic groups. As a result of some taxonomic bias in the priority species list, the species chosen were primarily moths and vascular plants, but also include bees, bryophytes, carabid beetles and spiders. It should be noted that, in addition to lowland heath, broadleaved woodland or calcareous grassland, a number of the species are also listed as being associated with other habitats (e.g. lowland farmland). One broadleaved woodland species was removed from analysis because there were two sub-species present in the north of the UK, with different habitat associations. None of the other species in the initial long-list were associated with broadleaved woodland, therefore, an additional lowland heath species was randomly selected, giving a total of 30 species (Table 1).

2.2 Bioclimate models

For each of the 30 species, we obtained species occurrence records across Great Britain (N. Ireland was excluded due to a paucity of data) between 1970-89, or 1970-86 for vascular plants, to be consistent with the start and end dates of major Atlases. Using records from more recent periods would potentially have included many more data from species already showing climate-driven range changes (Thomas *et al.* 2011; Mason *et al.* 2015). Therefore, we restricted our analysis to this 'historic baseline' period (Thomas *et al.* 2011). The data are collected by species recording schemes and societies and collated by the BRC. For many taxa, spatial and temporal recording effort varies, although efforts are made by all schemes to ensure that coverage is as complete as possible at the hectad level before producing national atlases. Therefore, standardisation of survey data is necessary in the analysis of these data. We used the program FRESCALO (Hill 2011) to produce estimates of recorder effort for each 10km square for each species. A 10km scale was selected as a compromise between ecological relevance and statistical power; at finer spatial scales there are insufficient species records across Great Britain to conduct meaningful analyses for the 30 threatened species considered here.

FRESCALO assesses recorder effort by comparing observed species to those expected from nearby neighbourhoods that have a similar ecological composition. For most taxonomic groups, compositional similarity was assessed using vascular plant community data using the method described in Hill (2011). For vascular plants, to avoid circularity, we assessed compositional similarity using the proportion of different land cover types in hectads using CEH LCM 2000 land cover map (Fuller *et al.* 2002). We calculated recorder effort as the proportion of species observed in a 10km square (hectad) relative to the total number of species expected. These estimates were then incorporated into bioclimate models as a model of the observation process hierarchically linked to the species' detection/ non-detection data (Beale *et al.* 2014).

To represent the spatial variation in climate that would be used to describe observed species distributions, four bioclimate variables were calculated at 10 km × 10 km resolution using 1961-

1990 averages: (i) mean temperature of the coldest month (MTCO): a measure of winter cold, (ii) growing degree days (GDD5): a measure of the plant growth season, (iii) the coefficient of variation of temperature (cvTemp): a measure of seasonality, (iv) soil moisture (soilWater): a measure of moisture availability. These four variables capture much of the existing bioclimatic variation, balancing ecological importance against statistical considerations, in particular, the need to avoid simultaneously fitting several strongly correlated covariates. All four variables are known to correlate with a wide variety of species distributions (Berry *et al.* 2002; Walmsley *et al.* 2007; Beale *et al.* 2008; Beale *et al.* 2014) and can also be considered as representative of a package of correlated variables, rather than just as individual variables. All variables were calculated from monthly mean temperature (°C), cloud cover (%) and total rainfall (mm) on a 5 km × 5 km grid from the UK Met Office (<http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/>). MTCO was calculated by simply finding the lowest monthly temperature for each cell. GDD5 was calculated by fitting a spline to mean monthly temperatures for each cell to convert monthly data to daily estimates, and then summing the accumulated daily temperature above 5°C. cvTemp was calculated by converting mean monthly temperatures to °K, and then dividing the standard deviation by the mean for each cell. Finally, soilWater was calculated following the bucket model described by Prentice *et al.* (1993), which takes inputs of temperature, rainfall, % sun/cloud and soil water capacities, then calculates the soil water balance over the year for each cell.

To relate species distributions to climate, we used a model described in Beale *et al.* (2014) that accounts for both spatial autocorrelation in large-scale species distribution data and spatial variation in observer effort (Beale *et al.* 2008). We applied a Bayesian, spatially explicit (conditional autoregressive) generalised additive model (GAM) to species distribution data. This has been shown to generate valid statistical associations between climate and distribution whilst simultaneously accounting for other, non-climatic processes, and fits flexible relationships between species occurrence and the climate data (Beale *et al.* 2014).

Future projections of climate change were based on the UK Climate Projections (UKCP09) for 2070-2099 for the Intergovernmental Panel on Climate Change's (IPCC) medium emission A1B scenario, which is more realistic, given current emissions trajectories, than the low emission B1 scenario (International Energy Agency 2012; Sanford *et al.* 2014). Data were downloaded from the UKCP09 user interface and consisted of Spatially Coherent Projections with 11 regional climate model (RCM) ensemble members (<http://ukclimateprojections-ui.defra.gov.uk>). We assessed each of the 11 ensemble members separately and used the median projection across these. Suitable species data and associated climate data were only available for Great Britain, meaning future climate projections in some areas of S. England were extrapolations into non-analogue parameter space with high associated uncertainty indicated by our bioclimate models. We did not incorporate land use change projections (e.g. Verburg *et al.* 2008; Verburg *et al.* 2010) into our future scenarios because our primary research question concerns the relevance of current conservation strategies (and land use) in the face of projected climate change. Incorporating land use change, besides the substantial additional uncertainty in these projections, would lead to two aspects varying, making it difficult to make a clear assessment of the adequacy of current conservation in the face of a changing climate. Therefore, for this study, it made sense to focus on projections of changes in climatic suitability of species and consider land use change as a potential policy response (i.e. through the conservation/adaptation actions explored here).

2.3 Delineating climatic suitability zones

For each species, we mapped current distribution, modelled current suitable climate space from the climate envelope model linking climate to occurrence, and projected future suitable climate space in 2070-2099. Our aim was to delineate areas of *New climate space* (not currently climatically suitable

but projected to be suitable in the future), *Climate overlap areas* current (climatically suitable and projected to be so in the future), *Adversely sensitive areas* (currently climatically suitable but projected to be unsuitable in the future; Figure S1 in Appendix A) following the work of Oliver *et al.* (2012; 2015).

Suitability of climate space is a continuous variable; specifically, the probability of species occurrence given the observed or projected climate conditions in any 10km grid cell. Therefore, we needed a ‘threshold’ value to define a significant change in climatic ‘suitability’. We selected an arbitrary threshold for change of 20% of the maximum estimated probability of occurrence in the historic period (1970-89, or 1970-86 for vascular plants), which we call P_x . A relative measure was used rather than an absolute percentage probability in order to standardise for differences in detectability between species. *Adversely sensitive areas* were identified as areas where the species was present with probability greater than P_x in the historic period, but then suffered a decrease in probability of magnitude greater than P_x ; *New Climate Space* was identified where the species experienced an increase in probability of occurrence greater than P_x ; *Climate Overlap Areas* were identified where the species was present with probability greater than P_x in the historic period and did not suffer declines or increases in probability of magnitude greater than P_x . The only exception to this was that 10km cells with observed presence records between 1970-1989 (1986 for vascular plants) outside of the modelled suitable climate space (i.e. in a few cases where the climate envelope model had made omission errors) were included as climatically suitable with an adjusted probability greater than P_x .

Figure 1 gives an example of these maps of suitable climate space and how future projections are used to delineate different climatic suitability zones. In this case, for the species *Bombus ruderarius* the threshold value, P_x , was 0.196 (0.979 x 0.2), where 0.979 is the maximum modelled probability of occurrence in the historic period. Hence, adversely sensitive areas were identified as those with a probability of greater than 0.196 in the historic period but with subsequent declines in probability projected by 2070-99 of more than 0.196 (the figure legend shows the minimum decline in this category was actually 0.242). New climate space was identified as areas with subsequent projected increases in probability of occurrence of greater than 0.196. Climate overlap areas had a probability of occurrence greater than 0.196 in the historic period, and no projected changes in probability greater in magnitude than 0.196.

We also assessed uncertainty in delineation of climatic suitability zones from climate envelope models by calculating the 95% confidence intervals of the modelled historic probability of occurrence and repeating the process above; an example is shown in Figure 2.

Accompanying maps used to delineate the climatic suitability zones for each species can be found in the supplementary material, similar to the example in Figures 1 and 2 but for all 30 species. Appendix B contains maps of current distribution, current modelled climatic suitability, projected climatic suitability 2070-99 and change in climatic suitability. Appendix C contains maps of projected climatic suitability taking into account uncertainty in the historic period [95th percentiles].

2.4 Trends in species' frequency of occurrence

Trends in the frequency of occurrence of species were derived from species occurrence records collated by the Centre for Ecology & Hydrology (CEH) Biological Records Centre, as part of a project funded by Natural England (Pearce-Higgins *et al.* 2015). Trends were calculated for 1970-99 but only within a species' ‘historic range’ (defined by the distribution of a species from 1970 to 1989, or 1986 for vascular plants) in order to exclude changes in newly colonised regions, as follows. For each species, a generalised linear mixed model (GLMM) with binomial error structure was fitted to the presence or absence of species during a site visit, with year as the covariate and

1km grid cell as a random effect (Roy *et al.* 2012). A ‘site visit’ was defined as a unique combination of date and 1km grid cell from all records of species in a taxonomic group recorded by a given recording scheme (Table 1). These data were filtered, first removing all site visits where fewer than four species were listed; second, excluding grid cells that had visits in fewer than three years between 1970 and 2009. These steps dealt with variation in recorder effort by restricting analyses to well-sampled grid squares with repeat visits. This approach has emerged as robust and statistically powerful in a simulation study comparing different methods (Isaac *et al.*, in review) and was used in the recent UK State of Nature Report (2013).

2.5 Using the decision trees

As the climate change adaptation framework (Oliver *et al.* 2012; Oliver *et al.* 2015) is intended for use by conservation advisers and managers, we demonstrate its rapid deployment at a national scale by relying on readily accessible and easily interpreted sources of information (Table 2). Most sources are published and publicly available. The exception is the bioclimate models and the trends in species frequency of occurrence for which methods are described above.

For each of the three climatic suitability zones and for each species, we used the appropriate decision tree(s) to identify recommended climate change adaptation actions (Figures S2-S4 in Appendix A, as described in Oliver *et al.* (2012, 2015). All three decision trees were used where a species’ current suitable climate space included adversely sensitive areas, and climate overlap areas, and new climate space areas were projected (see Figure S1 panel (a) in Appendix A). Only two decision trees were considered where a species’ current suitable climate space was disjunct from new climate space areas (i.e. there were no climate overlap areas Figure S1 in Appendix A panel b), and only one decision tree was addressed where current suitable climate space and projected future climate space completely coincided as a climate overlap area (Figure S1 Appendix A panel c).

Projections of future climate space were tempered by consideration of the availability of suitable land cover (as determined from habitat associations documented in Webb *et al.* 2010), including consideration of relevant geology for species of calcareous habitats. Wherever answers to questions in a decision tree were uncertain, or varied between areas within the climate zone, we followed both resultant paths through the tree. For each species, tables describing how every question in the decision framework was answered along with supporting evidence can be found in the supplementary material (Appendices D-F). To account for uncertainty in projections of climatic suitability for species (Appendix C), we highlight in the results tables (Appendices D-F) any substantial differences in the location of climate zones and subsequent recommended actions under the 95% confidence intervals compared to the median projected climatic suitability.

2.6 Comparing recommended conservation and climate change adaptation actions

We compared adaptation actions identified by the decision framework in different climatic suitability zones to current conservation actions recommended for each of the species by the UK statutory conservation body JNCC. To allow comparison, JNCC conservation actions described on the JNCC UK species pages (<http://jncc.defra.gov.uk>) were grouped into categories used in the climate change adaptation decision framework of Oliver *et al.* (2012) (e.g. ‘in-situ management’ is the category for actions to manage and protect existing habitat in order to improve habitat quality, conserve heterogeneity, and reduce or remove other non-climate related threats). The full explanation of each of these actions can be found in Appendix G. Details of JNCC’s recommended conservation actions for each species and the category that we allocated are included in Appendices D-F. In some cases, the location of conservation actions was specified by JNCC (e.g. “Maintain or restore traditional – no fertiliser, no herbicide, moderate autumn/winter grazing – pasture management for all remaining extant calcareous pasture sites to ensure that they are in favourable condition.”), whilst in others it was not (e.g. “Develop large-scale landscape processes and

mechanisms that will support and encourage the evolution currently operating in this genus”). Where the location was not specified, we assumed that this infers that the actions recommended by JNCC were intended for the species current or former range rather than across the whole of Great Britain. We believe that this is a reasonable assumption because local biodiversity action plans are most likely to promote actions for a given species if it occurs in that locality or has done so in the recent past. There is only one exception where JNCC recommended monitoring to find new populations of a species. In this case, we assumed this action is intended to occur in all three climatic suitability zones.

3. Results

3.1 Comparison of recommendations from the UK statutory conservation body and the climate change adaptation decision framework

We produced frequency plots of existing conservation recommendations (from JNCC, the UK statutory conservation body) versus the adaptation actions keyed out using the decision framework across the three climatic suitability zones (Figure 3). There were a number of similarities between the recommendations. First, the need for ‘monitoring and research’ was the most frequently recommended action across species in both approaches. Second, ‘in-situ management’ was often the next most frequently recommended action across species.

However, there were also a number of key differences between the two approaches. First, the action to ‘buffer edge impacts’, referring to managing the area around existing habitat patches to reduce negative impacts from their surroundings, was often identified by the climate change adaptation decision framework but not as a conservation action by JNCC. The statutory conservation body placed greater emphasis on ‘manage matrix’ without explicitly considering the need to buffer habitats. Second, conservation actions recommended by JNCC were focused almost exclusively within species’ existing ranges (i.e. climate overlap or adversely sensitive areas; Figure 3a and 3c). In contrast, the climate change adaptation decision framework identified a range of actions in areas of projected new climate space, including ‘buffer edge impacts’, ‘in-situ management’, ‘restore/create habitat’ and ‘translocate’ (Figure 3b). Third, in adversely sensitive areas the climate change adaptation decision framework identified fewer actions than are recommended by JNCC. However, the decision framework did recommend ‘accept local loss’, which was never proposed by JNCC. ‘Accept loss’ is only keyed out systematically by the decision trees after all relevant factors that would lead to other options have been fully considered. As such, the decision framework does identify a need to implement in situ management and/or to buffer edge impacts in adversely sensitive areas, and/or to focus efforts on populations in adjacent regions with suitable climate space. It should be noted that ‘accepting local loss’, does not mean giving up on a species altogether. Further knowledge of the species may suggest an alternative solution locally. However, the decision tree does assume that priority should be given to maintaining populations in places with the best long-term chance of persistence.

3.2 Comparison of climate change adaptation actions across habitat types

We also compared adaptation actions identified by the climate change adaptation decision framework across the three habitat types (Figure 4). There were some minor differences in the balance of actions between habitat types. For example for calcareous grassland, habitat restoration or creation of new habitat beyond existing sites were much less frequently recommended as priorities (due to the greater emphasis on in-situ management and increasing size of existing patches). However, on the whole there were more similarities than differences in the balance of actions across habitat types. For example, for all habitat types there was an emphasis on monitoring and research, in-situ management and restoration and habitat creation in the wider landscape. Across all three habitats, translocation of species was occasionally recommended as a possible

option in new climate space, as was accepting local loss of some populations in adversely sensitive regions.

4. Discussion

This study compared recommended actions from a statutory conservation agency with those in a published climate change adaptation decision framework (Oliver *et al.* 2012; Oliver *et al.* 2015) for 30 threatened species. Our aim was to assess whether current conservation recommendations for threatened species are likely to remain fully appropriate under future climates. Our comparison of the two approaches found a number of similarities but also key differences, which may have important implications for designing effective biodiversity conservation strategies.

4.1 Recommendations that stay the same under both approaches

An obvious similarity between the approaches is that both highlight a pressing need for monitoring and research. For many threatened UK species there is insufficient knowledge about species' current status, their habitat requirements or the relative importance of different threats to species. Second, both sets of actions identify the key importance of in-situ management within species' historic ranges. This reflects the emphasis in both approaches of addressing threats to existing populations before considering actions aimed at connecting populations. From a climate change adaptation perspective, in-situ management increases the resilience of populations and may also promote colonisation through increasing propagule pressure (Heller & Zavaleta 2009; Hodgson *et al.* 2009).

4.2 Recommendations that differ when considering climate change

Despite the similarities above, our comparison did reveal key differences between the balance of actions and in where actions should be carried out. For example, the climate change adaptation decision framework identified the need for effort in areas of potential new climate space and placed less emphasis on actions in adversely sensitive areas. This reflects the recognition of the dynamic nature of species' climate space and the consequent need for a dynamic approach to nature conservation (Smithers *et al.* 2008). For example, management, restoration and creation of habitats beyond species' current ranges, and occasionally even translocation, may be necessary to facilitate species' range shifts (Hoegh-Guldberg *et al.* 2008; Seddon *et al.* 2009). Similarly, an increased focus on actions outside of adversely sensitive areas, arising from use of the decision framework, is a recognition of the need to prioritise action to where future negative climate pressures on species are lower and there is greatest potential conservation gain.

Even in the same climatic suitability zones, there were some differences in the balance of actions recommended by the statutory conservation agency and by the climate change adaptation decision framework. For example, whilst the statutory conservation agency did not explicitly promote buffering of edge impacts, the climate change decision framework identifies it as an important first step in reducing other threats not linked to climate change. Additionally, there was less focus on matrix management and habitat creation in the wider landscape under the climate change decision framework. This reflects the decision framework's closer adherence to the latest conservation consensus for increasing site quality and size before addressing intervening landscapes (Lawton *et al.* 2010).

The differences between the two approaches are important because they suggest that the static approaches, currently underpinning existing conservation strategies could potentially fail to maximise species persistence in a changing climate. Of course, there are large uncertainties when dealing with climate change impacts, but we propose that these are not a valid reason to ignore the

changes in climatic suitability that are already manifesting themselves in the behaviour, abundance and distribution of species (Parmesan & Yohe 2003; Chen *et al.* 2011; Devictor *et al.* 2012).

4.3 Dealing with uncertainty in climate projections

In using the decision framework to identify and prioritise actions, the uncertainty in climate space projections must be taken into account (Kujala *et al.* 2013). There are issues with relying on bioclimate models and due caution is required in their interpretation and use, especially when modelling rare species (Pearson & Dawson 2003; Hampe 2004; Pearson & Dawson 2004; Beale *et al.* 2008). In this study, the projected suitable climate space identified could potentially be erroneous because: a) the models are based solely on data from Great Britain (e.g. they may not identify areas that will become too hot, as the data does not include the southern range margin of species distributions), b) there are additional limits to distribution other than climate (e.g. geology, land cover and management, interactions with other species) and current distribution data may not be comprehensive, such that modelled climate space may appear narrower than the true climatic niche (Britton *et al.* 2001; Luoto *et al.* 2007; Illán *et al.* 2010), c) inputs to the model do not capture aspects of climate critical to the species (as may be indicated by the current distribution being greater than modelled current climate space), or d) species current distributions are not at equilibrium with climate (e.g. rare and chance events may have led to their survival in refugia or to colonisation, such that climate is not the dominant factor responsible for their location; Svenning & Skov 2004; Araújo & Pearson 2005) .

In our analyses, we have done our best to deal with these issues. For example, we used a state-of-the-art bioclimate modelling method, which accounts for spatial autocorrelation in explanatory variables (Beale *et al.* 2014), and we extended this to account for spatio-temporal variability in recorder effort using the FRESALLO method (Hill 2011). In addition, we did not simply use mean estimates of climate suitability, but assessed the uncertainty bounds of estimated probabilities of occurrence. Nevertheless, appropriate caution should be taken when using these bioclimate model outputs. For example, in this project, due to data availability, models were fitted at coarse hectad (10km square) resolution and missed finer-scale climatic variability. Thus, although the decision framework can suggest accepting local loss of species populations within adversely sensitive areas, due account should be taken of the potential presence of more local topographic refuges. In the absence of finer-scale models, this means that practitioners might wish to adopt a more conservative approach to adversely sensitive areas where there is high topographic variability and also run species through the decision trees for climate overlap areas or new climate space to identify potential relevant adaptation actions. In Oliver *et al.* (2012), we also emphasise the need for adaptive management and encourage users to revisit the decision framework as and when new information becomes available. For example, in future, improved modelling techniques might better identify topographic refugia and more closely prescribe which decision trees should be consulted locally.

For some species with fewer data available, we encountered substantial uncertainties in the modelling of suitable climate space. For example, the 95% uncertainty bounds on probability of suitable climate space for the Olive Crescent moth *Trisateles emortualis* suggested that whole of Great Britain might become either an adversely sensitive area or new climate space. Although this is an extreme example, nonetheless, we must recognise that, whilst bioclimate models provide very helpful signposts, they will never be able to tell us with precision about what is going to happen to which species, where and when, particularly at a local scale, nor do current models adequately account for inter-specific interactions (Walmsley *et al.* 2007). In addition, they do not address the indirect impacts of climate change on use of land and other resources, which could be more damaging than the direct impacts (Smithers *et al.* 2008). Therefore, it will be essential to monitor species responses as climate change proceeds.

A second limitation encountered during the process of running species through the climate change adaptation decision framework was that there was often a lack of species data with which to answer certain questions. This meant that we had to take multiple routes through the tree, leading to uncertainty in the most appropriate actions recommended. Therefore, it is clear that further monitoring and research into species is essential to refine conservation and climate change adaptation advice.

4.4 Future directions

In this study, we assessed species associated with three broad habitat types (lowland heath, broadleaved woodland and calcareous grassland). It should be noted that sample sizes for species associated with each habitat type were very small ($n=9-11$), and, therefore, generalisations should be made with considerable caution. Nevertheless, a consistent pattern emerging seems to be a similarity of recommended actions across species. This suggests that a more habitat-focused approach could be adopted to enable climate change adaptation for multiple species. For example, in-situ management actions in grassland might include generic actions, such as grazing to maintain heterogeneity of the grassland sward, which is likely to aid adaptation of many grassland species.

Future work building on this current study might, therefore, usefully run a greater number of threatened species through the framework to explore patterns by taxonomic group, habitat, and guilds of species with similar ecological traits (e.g. habitat area requirements and/or dispersal abilities). In each case, actions could be mapped to identify whether different suites of actions are associated with particular localities or regions. Adaptation actions identified could also be considered holistically across all threatened species in order to identify the overall priorities for the UK and by region that emerge from deploying the decision framework. Once prioritised, actions would need to be considered in relation to the social, economic and political context, upon which successful implementation would ultimately depend (Burch *et al.* 2014; Macgregor & van Dijk 2014). More broadly, the framework could be used in relation to keystone species, umbrella species or generic focal species (Simberloff 1998; Watts *et al.* 2010).

5. Conclusions

Conservation is a philosophy; it is not ruled by science but can be informed by it. A systematic approach to the identification of priorities, such as provided by the decision framework used here, cannot and should not seek to equalise or negate organisations' or individuals' values. However, we hope that the decision framework's rapid, repeatable and transparent method, which facilitates adaptive management, means that it can play an important role in "negotiating the transition from past to future in such a way as to secure the transfer of maximum significance" (Holland & Rawles 1993). Consensus is building that conservation needs to shift from protecting the 'status quo' to promoting a dynamic ecological response to environmental change (Ellis 2011). We hope that decision support tools, such as the climate change adaptation framework used here, can aid such a transition.

Acknowledgments

We are grateful to the dedicated members of the many national species recording schemes and societies for the natural history, monitoring and occurrence data on which these analyses were based. JNCC and the UK Natural Environment Research Council fund the collation of these data through the UK Biological Records Centre. Thanks to Mike Morecroft, Humphrey Crick and James Pearce-Higgins for comments on the project report for Natural England, under which this work was partly funded (contract ref NECR175). Also, thanks to Tom August and Nick Isaac for calculating species trends as part of this project.

Data Accessibility

Data for species distributions are available from the NBN Gateway <https://data.nbn.org.uk/> .
Derived bioclimate model maps are being made available through the NERC Environmental Informatics Data Centre. Sources for other datasets used are listed in Table2.

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<http://publications.naturalengland.org.uk/publication/30025?category=65029>.

Tables

Table 1, Species considered in the analysis, including their habitat association from Webb *et al.* (2010) and their taxonomic grouping.

Species Latin name	Common name	Habitat association	Taxonomic group
<i>Euphrasia pseudokernerii</i>	Chalk Eyebright	Chalk grassland	Vascular plants
<i>Adscita staites</i>	Forester moth	Chalk grassland	Moths
<i>Carex ericetorum</i>	Rare Spring-sedge	Chalk grassland	Vascular plants
<i>Hadena albimacula</i>	White spot moth	Chalk grassland	Moths
<i>Heliophobus reticulata</i>	Bordered Gothic	Chalk grassland	Moths
<i>Herminium monorchis</i>	Musk Orchid	Chalk grassland	Vascular plants
<i>Polia bombycina</i>	Pale Shining Brown Moth	Chalk grassland	Moths
<i>Pulsatilla vulgaris</i>	Pasque flower	Chalk grassland	Vascular plants
<i>Scotopteryx bipunctaria</i>	Chalk Carpet Moth	Chalk grassland	Moths
<i>Shargacuculia lychnitis</i>	Striped Lychnis moth	Chalk grassland	Moths
<i>Cephalanthera damasonium</i>	White Helleborine	Broadleaved woodland	Vascular plants
<i>Cossus cossus</i>	Goat Moth	Broadleaved woodland	Moths
<i>Cyclophora porata</i>	False Mocha Moth	Broadleaved woodland	Moths
<i>Melittis melissophyllum</i>	Bastard Balm	Broadleaved woodland	Vascular plants
<i>Monocephalus castaneipes</i>	Broad Groove-head Spider	Broadleaved woodland	Spiders
<i>Paracolax tristalis</i>	Clay Fan-foot Moth	Broadleaved woodland	Moths
<i>Saaristoa firma</i>	Triangle Hammock-spider	Broadleaved woodland	Spiders
<i>Trichopteryx polycommata</i>	Barred Tooth-striped Moth	Broadleaved woodland	Moths
<i>Trisateles emortualis</i>	Olive Crescent Moth	Broadleaved woodland	Moths
<i>Aleucis distinctata</i>	Sloe Carpet	Lowland Heath	Moths
<i>Andrena tarsata</i>	Tormentil Mining Bee	Lowland Heath	Bees
<i>Bombus muscorum</i>	Moss Carder-bee	Lowland Heath	Bees
<i>Carabus monilis</i>	Necklace Ground Beetle	Lowland Heath	Carabid beetles
<i>Chamaemelum nobile</i>	Chamomile	Lowland Heath	Vascular plants
<i>Dicranum spurium</i>	Rusty Fork-moss	Lowland Heath	Bryophytes
<i>Haplodrassus dalmatensis</i>	Heath Grasper	Lowland Heath	Spiders
<i>Illecebrum verticillatum</i>	Coral necklace	Lowland Heath	Vascular plants
<i>Mentha pulegium</i>	Pennyroyal	Lowland Heath	Vascular plants
<i>Odynerus melanocephalus</i>	Black-headed Mason Wasp	Lowland Heath	Wasps
<i>Xestia agathina</i>	Heath Rustic	Lowland Heath	Moths

Table 2. Sources of information used to answer questions in the climate change adaptation decision framework.

Data source	Details
1	Trends in species distribution extent from 1970-2009 from Natural England Report contract ref. 24800 (see Methods section)
2	Bioclimate maps (see Methods section)
3	JNCC UK species pages (http://jncc.defra.gov.uk/page-5163)
4	Webb, J.R., Drewitt, A.L., & Measures, G.H., 2010. Managing for species: Integrating the needs of Englands priority species into habitat management. Part 1 Report. <i>Natural England Research Reports, Number 024</i> : http://publications.naturalengland.org.uk/publication/30025?category=65029
5	Centre for Ecology and Hydrology Land Cover Map 2007 for broadleaved, mixed and yew woodland, calcareous grassland and heather dwarf shrub (Centre for Ecology and Hydrology 2011)
6	Map of limestone and chalk substrate from British Geological Survey (BGS) Digital Geological Map Data of Great Britain - 50k (http://data.gov.uk/dataset/digital-geological-map-data-of-great-britain-50k-digmapgb-50-surface-version-5-18)
7	Condition of Sites of Special Scientific Interest: http://www.sssi.naturalengland.org.uk/Special/sssi/report.cfm?category=N
8	Database of insects and their foodplants (DBIF; http://www.brc.ac.uk/dbif/homepage.aspx)
9	National Biodiversity Network gateway: http://data.nbn.org.uk/

Figure Legends

Figure 1, Maps showing a) historic distribution of an example species, *Bombus ruderarius*. Black crosses show submitted records, coloured squares show modelled probability of historic (1970-1990) occurrence based on relationships with climate variables (see main text); b) Projected probability of occurrence under A1B scenario; c) The change in modelled probability of occurrence coloured to delineate different climatic suitability zones (see main text) - yellow and red squares show areas of new climate space, white squares show areas of climate overlap, blue squares show adversely sensitive areas and grey squares indicate areas climatically unsuitable in both periods.

Figure 2, Maps showing a) Projected change in modelled probability of suitable climate space for *Bombus ruderarius* coloured to delineate different climatic suitability zones (the same as Figure 1c); b) and c) Projected future change in probability of suitable climate space for *Bombus ruderarius* in relation to the upper and lower 95% confidence intervals for the modelled historic probability of occurrence. Colour coding as in Figure 1.

Figure 3, Frequency of conservation actions recommended for 30 threatened species by a UK statutory conservation agency (JNCC) compared to those identified by the climate change decision framework. Actions are ascribed to areas of each species' projected climate space (panels a, b and c).

Figure 4, Frequency of climate change adaptation actions recommended by the decision framework for 30 species with different habitat associations. Actions are ascribed to areas of each species' projected climate space (panels a, b and c).

Figures

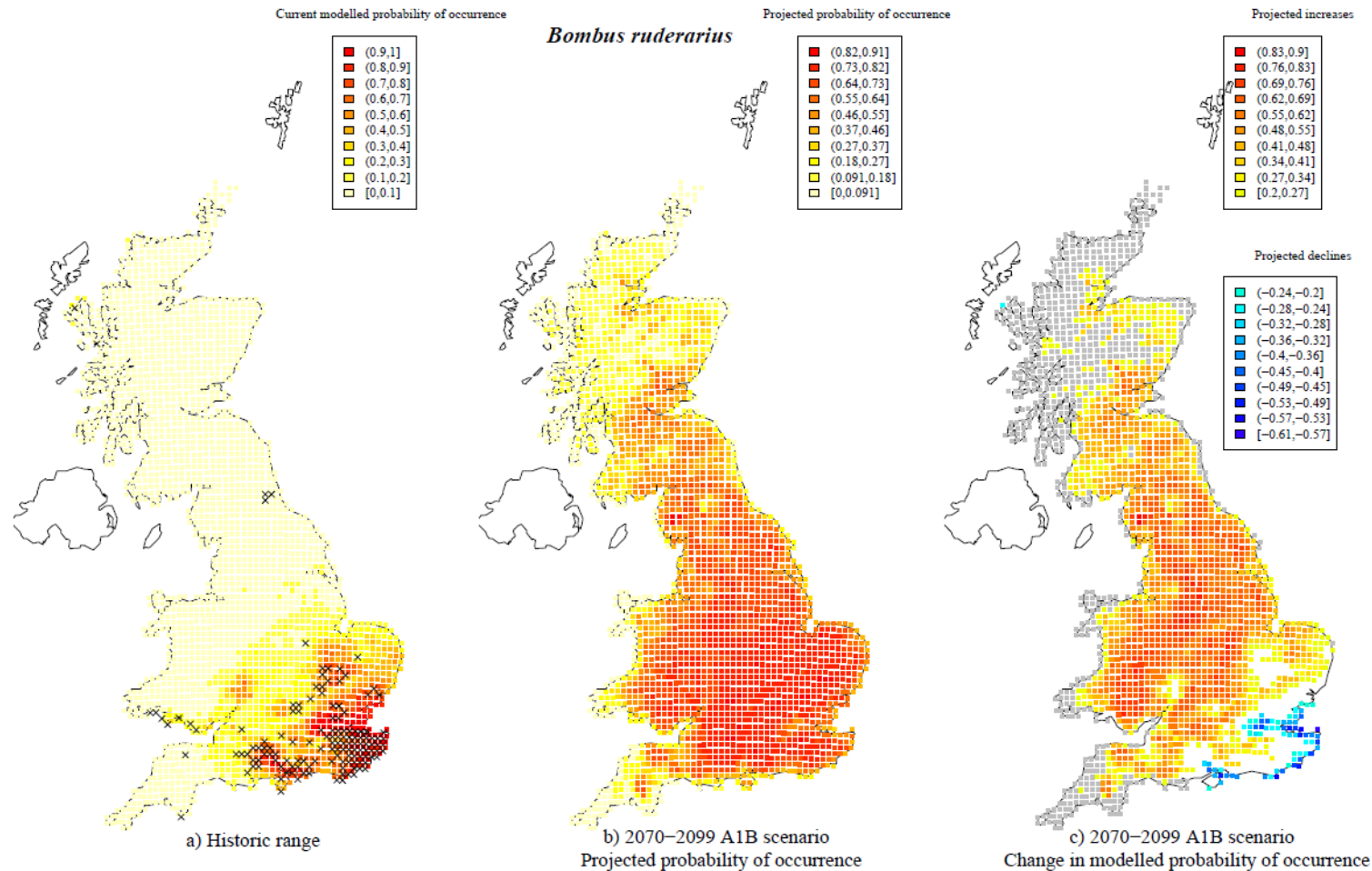


Figure 1, Maps showing a) historic distribution of an example species, *Bombus ruderarius*. Black crosses show submitted records, coloured squares show modelled probability of historic (1970-1990) occurrence based on relationships with climate variables (see main text); b) Projected probability of occurrence under A1B scenario; c) The change in modelled probability of occurrence coloured to delineate different climatic suitability zones (see main text) - yellow and red squares show areas of new climate space, white squares show areas of climate overlap, blue squares show adversely sensitive areas and grey squares indicate areas climatically unsuitable in both periods.

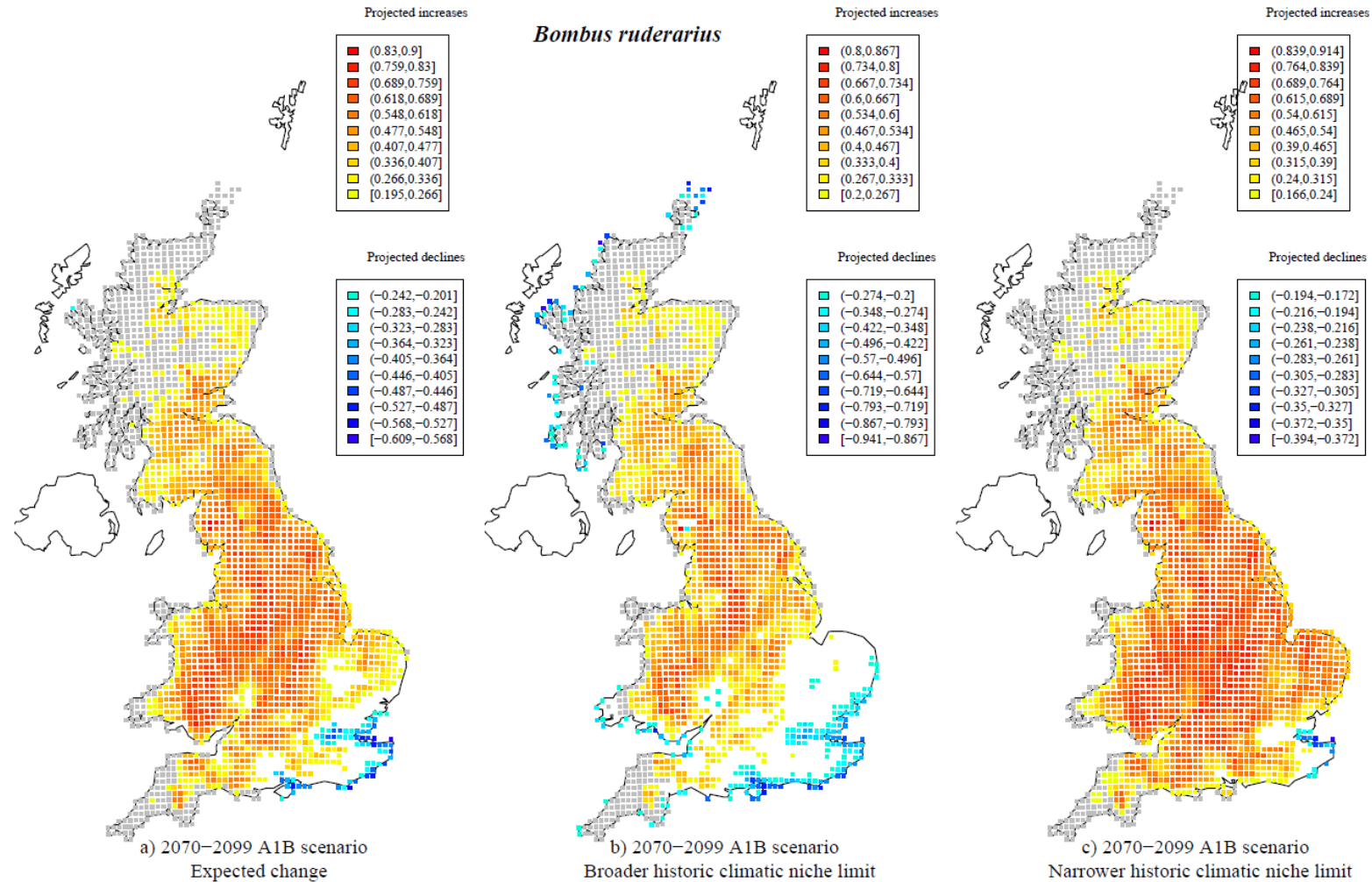


Figure 2, Maps showing a) Projected change in modelled probability of suitable climate space for *Bombus ruderarius* coloured to delineate different climatic suitability zones (the same as Figure 1c); b) and c) Projected future change in probability of suitable climate space for *Bombus ruderarius* in relation to the upper and lower 95% confidence intervals for the modelled historic probability of occurrence. Colour coding as in Figure 1.

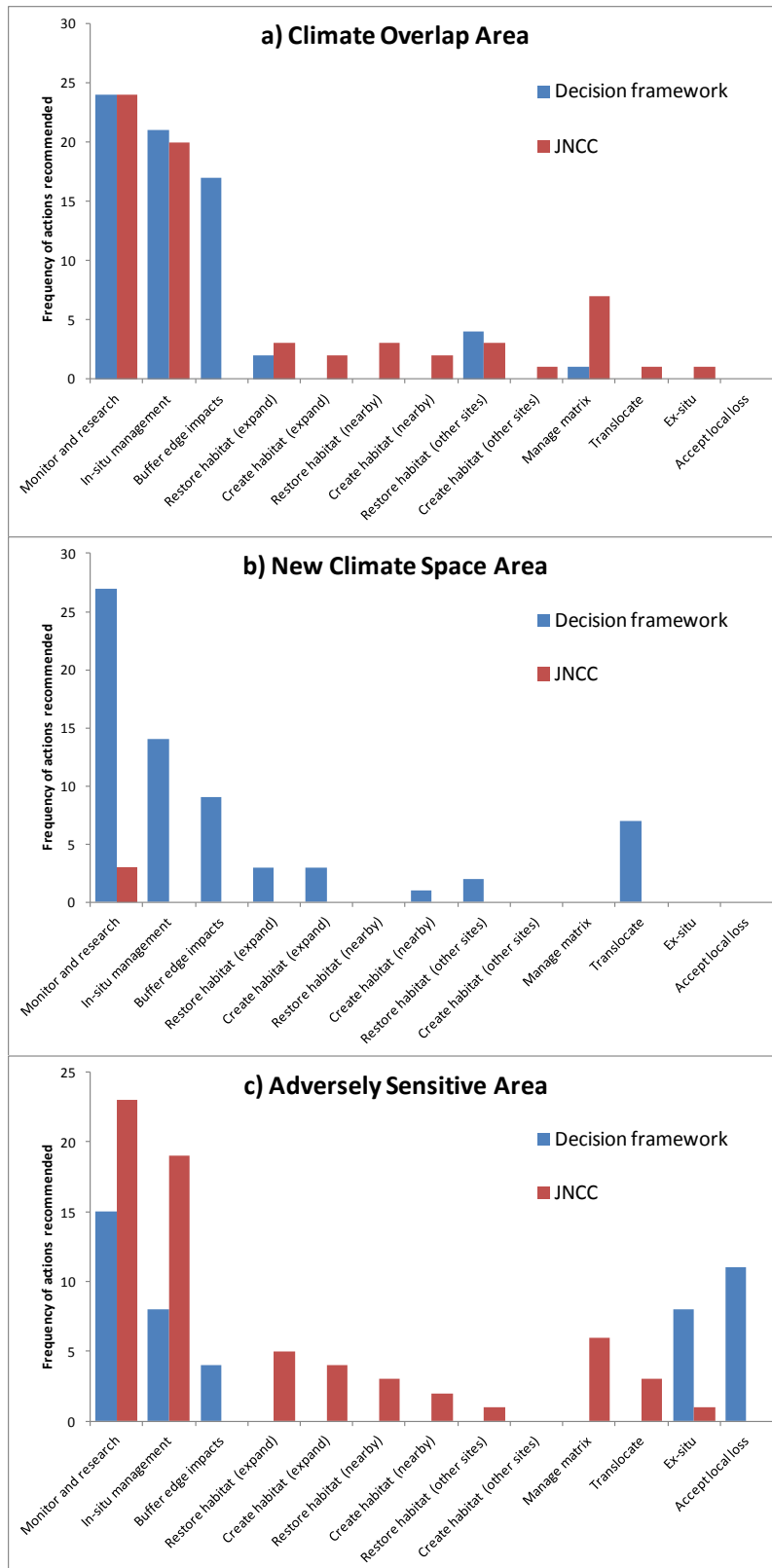


Figure 3, Frequency of conservation actions recommended for 30 threatened species by a UK statutory conservation agency (JNCC) compared to those identified by the climate change decision framework. Actions are ascribed to areas of each species’ projected climate space (panels a, b and c).

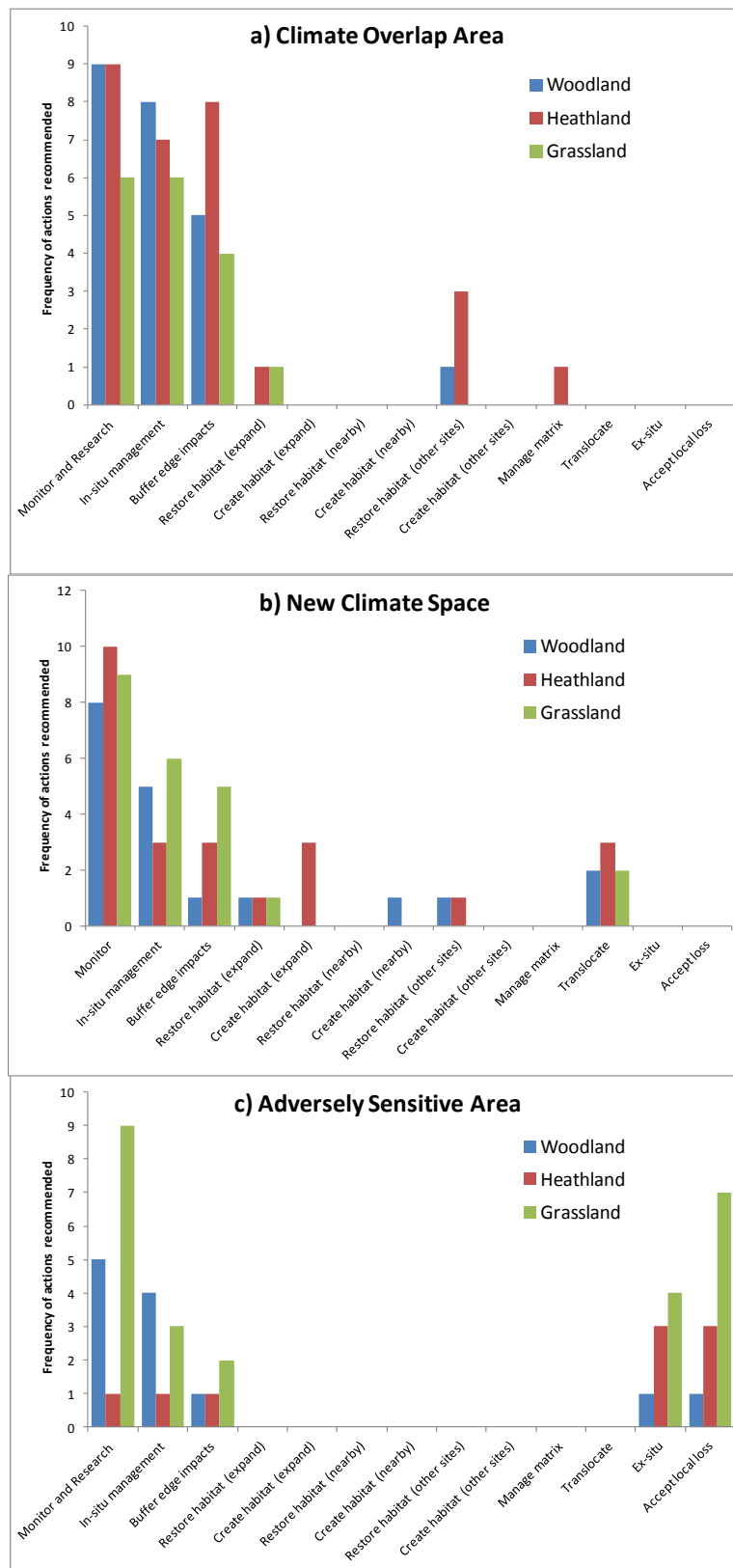


Figure 4, Frequency of climate change adaptation actions recommended by the decision framework for 30 species with different habitat associations. Actions are ascribed to areas of each species' projected climate space (panels a, b and c).