Natural England Commissioned Report NECR175

Research on the assessment of risks & opportunities for species in England as a result of climate change

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NATURAL ENGLAND

Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Background

There is already strong evidence for a wide range of impacts of climate change on England's wildlife, such as changes in distributions, phenology, community composition and habitat condition. The UK is one of the best recorded sites in the world for species distribution and clear shifts in the northern limits of some mobile animal groups have been identified, as well as redistributions to higher altitudes. In order to target conservation resources efficiently and effectively, Natural England has to prioritise action based on the rarity of species, their threats and their current rates of decline. As part of this, Natural England needs to understand how it can help species to adapt to climate change and to encourage species that might thrive under climate change if given the appropriate management.

This project aims to fill an important gap in our evidence base by using the latest modelling techniques and analytical frameworks to explore how species are likely to change their distributions (and for migratory birds, their population sizes) as a result of climate change. The analysis was undertaken for 3000 species of a wide range of terrestrial taxa (from vascular plants and bryophytes to spiders and beetles) and assesses the potential risks within their existing ranges as well as the opportunities that might be provided in new areas. A more detailed analysis was applied to 400 species, taking into account the factors that might exacerbate or mitigate the impacts of climate change. Finally a very detailed framework was applied to 30 species to explore the adaptation options that might be available to conservation practitioners.

The project thus provides a good evidence base for conservation practitioners to use within the context of their planning at national and local scales. It also demonstrates the value of the more detailed frameworks to provide additional information of value in addition to identifying potentially useful adaptation options.

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Further information

This report can be downloaded from the Natural England website: **www.gov.uk/government/organisations/natural-england**. For information on Natural England publications contact the Natural England Enquiry Service on 0845 600 3078 or e-mail **enquiries@naturalengland.org.uk**.

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Research on the assessment of risks & opportunities for species in England as a result of climate change

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Executive summary

- In this report we present an assessment of potential changes in the spatial distributions of over 3,000 plants and animals that occur in England resulting from projected climate change. We also consider some potential adaptation responses for different species.
- Using a basic framework which compared projected future distributional changes with recently observed changes, 640 (21%) of 3,048 species considered were classified as being at high risk from climate change under a 2 ˚C warming scenario, and 188 (6%) at medium risk. A greater number of these species could potentially expand their range in Great Britain, representing a medium or high opportunity for 486 (16%) and 1,164 (38%) species respectively, at this geographic scale. This is because more species reach their northern range margin in England than their southern range margin.
- This basic assessment excluded consideration of potential confounding and exacerbating factors, such as the availability of suitable habitat,and restricted dispersal ability, that might limit the ability of species to shift their distributions. As a result, these results may over-estimate the likely rates of change.
- A more comprehensive framework, which accounts for some of these potentially confounding and exacerbating factors, assesses the extent to which recently observed changes may be linked to climate change and provides an assessment of the confidence associated with each assessment was applied to 402 species. This analysis showed that a greater proportion of species (35 %) were at high or medium risk from climate change compared to 42 % likely to facing opportunity under a 2 ˚C warming scenario. This more detailed assessment improved the attribution of recent change to climate change, resulting in a greater proportion of species being regarded as likely to be only little affected by climate change at this geographic scale.
- While the confidence assessments for many of the species from the more comprehensive framework were rated as low, this was often because there was a lack of information on the likely influence of climate on species populations. This means that the results for individual species need to be treated with caution, but the overall patterns are likely to be robust due to the number of species assessed.
- A slightly greater proportion of species of current conservation concern (priority species listed under the Natural Environment and Rural Communities (NERC) Act), were regarded as being at risk from climate change (38%) than non-priority species, with fewer for which climate change may provide an opportunity (39 %) than other species.
- There was significant variation in the assessed vulnerability of different taxa to climate change. Bryophytes appeared to be under the greatest risk, whilst the majority of hymenoptera were regarded as likely to face an opportunity. This may, in part, reflect their predominantly northern/upland and southern/lowland distributions respectively. In most other taxa, a mixture of species was identified as being at 'risk' or facing opportunity.
- The greatest proportion of NERC priority species at risk from climate change occurred in upland habitats, where the majority of species were classed at high or moderate risk.
- An additional assessment for migratory bird species and species listed on Annex I of the EU Birds Directive found that northerly distributed breeding seabirds and upland

breeding birds were amongst those at the greatest risk of decline, whilst a number of southerly distributed species appeared likely to increase in abundance. Although many of these species-assessments were associated with low confidence, projected population declines for dotterel and curlew, and population increases for avocet, sanderling, little egret and Dartford warbler were associated with medium or high confidence, and are largely supported by other data and studies.

- There appeared to be little difference in the proportions of species in different risk categories associated with 2 and 4˚C global warming scenarios projected to 2070-2099, due to consistent direction and relatively small differences in the degree of temperature and precipitation change between these two scenarios for Britain, compared to changes against the 1960-90 baseline.
- It was clear that assessments should ideally be based upon distributional data from a wide geographical area in order to prevent the over-estimation of change that results from using distribution data from Great Britain only. The novelty of future projected climates for Great Britain means that ideally, species' distribution projections should incorporate data from Europe, otherwise a species might be projected to be unable to persist in an area when the climate was actually suitable. For most taxa, assessments in this study were based using only data from Great Britain. However, the general direction of projections for these species is still informative, but likely to tend towards greater distributional change.
- The application of this framework was associated with a number of significant challenges, particularly for taxa for which there may be spatial variation in recorder effort or poor recorder coverage, and for poorly studied taxa. These challenges are discussed, and need to be considered when these results are applied to making conservation decisions, although the analytical methods and full Thomas framework approach adopted allow these constraints to be accounted for during the risk assessment process as much as possible.
- There is considerable potential for management to improve the conservation status of species in the face of a changing climate. For birds, a detailed habitat-based assessment of key management actions is presented. Results from this emphasise the potential for site-based management to increase species' resilience to climate change, although further research is required to test the efficacy of these management approaches. For many other potentially range-expanding species, conservation action is required to protect and create suitable habitat for colonisation, or to address current conservation issues which may prevent the population occupying areas of increasingly suitable climate.
- A second, decision-support framework was used to prioritise adaptation actions in a more structured way for 30 non-avian taxa. This identified the need for monitoring and research to improve and inform decision making. I*n situ* management and buffering of edge impacts were also regarded as a priority, along with an increased focus on management outside of species' current range.
- This project deals largely with the potential for species ranges to change under climate change. It is however also important to recognise that much can be done to increase resilience to change within existing distributions and these results may help to focus efforts to do this, as well as identify opportunities to facilitate range expansion.

- The species-specific assessments of risks and opportunities to species as a result of climate change accompany this report.

Preface

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The world's climate is changing and the scientific and political consensus is that this it is "extremely likely" that human influence has been the dominant cause of the observed warming since the mid-20th century (IPCC 2013). The changes in global climate have already been reflected in the UK's climate, for example the long-running Central England Temperature record has shown an increase of *c*1°C since the 1970s (Jenkins *et al.* 2008). Climate models indicate that the global climate will continue to warm over the course of this century and the UK Climate Projections (known as UKCP09, Murphy *et al.* 2009) also consistently project average warming of between 2 and 7°C for the UK by 2100. In addition to changes in temperature, a number of other changes are projected by UKCP09; in particular, trends towards wetter winters and drier summers have consistently been indicated for the UK (Murphy *et al.* 2009).

The consequences of future climate change for England's wildlife are likely to be substantial – indeed, there is already strong evidence for a wide range of impacts such as changes in distributions, phenology, community composition and habitat condition (Morecroft & Speakman 2013). The UK is one of the best recorded sites in the world for species distribution and clear shifts in the northern limits of some mobile animal groups have been identified (Hickling *et al.* 2006), as well as redistributions to higher altitudes (e.g. Hill *et al.* 2002, Britton *et al.* 2009). The distributions of internationally important wintering shorebird populations in the UK have shifted east and north as winter climate has warmed (Austin & Rehfisch 2005). The evidence for plants and animals with limited mobility is less clear, although experimental evidence is beginning to show that some species may be limited from colonising suitable areas north of their current range due to poor dispersal (e.g. Marsico & Hellman 2009, Willis *et al.* 2009, Chen *et al.* 2011).

The *Biodiversity 2020* strategy for England (Defra 2011a), produced by the Government in response to both the Nagoya agreement of the Convention on Biodiversity and to the Government's Natural Environment White Paper *The Natural Choice: securing the value of nature* (Defra 2011b), includes Outcome 3 on species conservation: *By 2020, we will see an overall improvement in the status of our wildlife and will have prevented further human-induced extinctions of known threatened species.* In order to target conservation resources efficiently and effectively, Natural England has to prioritise action based on the rarity of species, their threats and their current rates of decline. As part of this, Natural England needs to understand how it can help species to adapt to climate change and to encourage species that might thrive under climate change if given the appropriate management.

Adapting to climate change, minimising risks and maximising opportunities, is an essential element of conservation as in many other areas of life (Hopkins *et al.* 2007, Smithers *et al.* 2008, Morecroft *et al.* 2012). Within England there is a broad national context for climate change adaptation set out by the National Adaptation Programme (Defra 2013), which includes a chapter on the natural environment. Natural England has made an assessment of risks to its work and has developed a plan to address them (Natural England 2012). An important aspect was the potential threat to species of conservation concern and how species recovery plans and action plans might be compromised. However, the assessment also noted that there may be opportunities for some species to increase in abundance or expand their range as a result of climate change. Natural England needs an evidence base that can help it design appropriate adaptation strategies for as wide a range of species as possible. Adapting to climate change takes conservation into uncharted territory: we cannot rely solely on lessons learnt in the past under different conditions. This is an area in which the need for good scientific evidence is particularly strong. This project forms part of a wider series of studies to help Natural England to develop its climate change adaptation strategies and practice. It focuses specifically on species, how their distributions may change as the climate changes and what the implications of these changes may be for their conservation.

Climate Envelope Modelling

All species have a range of climatic conditions in which they can exist, sometimes termed their climatic envelope. This differs between species and leads to the contrasting distribution patterns. The relationship between distribution and climatic variables can be modelled using a range of mathematical techniques (Pearson & Dawson 2003, Renwick *et al*. 2012), although these have been subject to criticism (Araujo & Rahbek 2006, Beale *et al.* 2008). These relationships can then be used to project future changes on the basis of climate change scenarios. This technique has been developed over the last twenty years in the UK, and projected changes in distribution are available for many species; one of the most influential projects of this sort was MONARCH (Modelling Natural Resource Responses to Climate Change, Berry *et al.* 2003).

Climate envelope modelling has proved a valuable guide to species sensitivity to climate change, but it has limitations which need to be understood when using its results. These include the following, but it should be noted that the new analytical techniques used in this report attempt to deal with a number of these limitations:

- If current distributions are determined largely by factors other than climate, such as soil conditions associated with a particular local geology, land management practices or by historical factors such as past persecution, the relationship between present day distribution and climate will be weak and of limited value in projecting future change (Davis *et al.* 1998, Crick 2004, Beale *et al.* 2008). In the cases of rare, localised species, it will simply not be possible to derive any relationship to climate.
- Climate change may result in climatic conditions for which there is no present day analogue, and projections based on present climate will be unreliable (Hossell *et al.* 2005).
- Climate and distribution are typically mapped at a large scale (tens of kilometres). The actual distribution of species may, in practice, be determined at a much smaller scale. So, for example, a mountain top species may be restricted to the coolest parts of a grid square, whereas the climate value for that square reflects an average (Trivedi *et al.* 2008, Seo *et al.* 2009).
- Distribution maps for some species may not be accurate. Britain has better datasets than most other countries, but there are still gaps in the distribution record in more isolated areas and for harder to identify and less charismatic groups of species.

- Local climate variations and microclimates may provide conditions in which a species can survive locally, where one would not expect it to on the basis of larger scale patterns in climate. These localised areas of suitable climate are sometimes termed microclimatic refugia (Suggitt *et al.* 2014).
- Climate envelope models indicate where climate conditions may be suitable, but not whether a species can reach a new potential location or whether other requirements such as habitat or food supply will be available there.
- Interactions between species may play a major role in determining climatic limits, for example a species may be able to survive in a warmer climate but in practice be outcompeted by others that are better suited to the new conditions.

Risks and opportunities frameworks

Climate envelope modelling provides a useful tool for assessing how species distributions of might change under different scenarios of climate change. However the assessment of risk or opportunity to species from the results of such modelling is not straightforward. Species may show both losses and gains, but in different parts of its range. Furthermore, as described above, other factors may be important drivers of their population changes which could confound the interpretation. To help overcome some of these issues, Natural England collaborated on a project, funded under NERC's UKPopNet programme, to develop a framework for identifying the species most at risk and those most likely to benefit from climate change. The framework was published by Thomas *et al.* (2011) and considers separately (i) changes within regions where a species has traditionally occurred and (ii) increases outside the species' former range (e.g. since 1970. The framework analyses measured changes in the existing and new range, as well as projected changes in each. It also considers questions around data adequacy and whether other factors might have affected species and whether factors might make the species more or less vulnerable to climate change. These assessments are then brought together into an overall assessment of risks and opportunities for each species.

Following on from this, a team also funded under the UKPopNet explored further how to help decide on the appropriate adaptation measures that might be necessary for species, given the levels of risks and opportunities identified under the Thomas *et al.* (2011) framework. This adaptation framework (Oliver *et al.* 2012) presents a series of decision trees that are based on where conservation action is required, i.e.: in areas where the climate is becoming less suitable; areas where the species is likely to persist, and areas where the species might expand.

This report

This report provides the results of analyses based around new modelling techniques that address statistical problems identified by Beale *et al.* (2008) and are better able to represent the relationship between distribution and climate (using a Bayesian approach and helping to control for variations in observer effort) to make improved projections of changes in a species' climate space and thus it's potential distribution.

One of the main aims was to undertake an analysis of the risks and opportunities posed by climate change for as many species that occur in England as possible. The widest range of available datasets was assessed for terrestrial species held by the Biological Records

Centre and the British Trust for Ornithology. Initial assessments showed that there were sufficient data to assess trends and for modelling for *c*. 3000 of the 5000 species datasets available. This is a substantially more comprehensive coverage than any previous initiative of this sort. A basic analysis on these 3000 species compared climate-based distributional projections with population trends over the past 40 years at the GB level. Importantly, it uses information about recent changes in actual distribution to give a better assessment of potential future risks and opportunities: if changes have already taken place that are consistent with the changes projected due to climate change, it is reasonable to infer that the risk or opportunity is greater.

However, this basic framework doesn't take into account the potentially confounding and exacerbating factors that might influence each species. The full Thomas *et al*. (2011) framework does this (to the extent that such information is available), as well as taking into account data quality issues, thus:

- it gives added weight to trends which are consistent with the likely impacts of climate change and for which there is published evidence of such links;
- it takes into account whether small population or distribution size might make the species more vulnerable;
- it considers whether interactions with other species or habitat changes might affect a species; and
- it also considers whether dispersal ability and habitat specificity might limit a species' ability to spread to new areas.

Such an analysis requires a much greater detail of knowledge and information and is more time consuming, so it was carried out for a subset of *c*. 400 species, including as many species as there were data for, that are listed as of principal importance for the conservation of biodiversity in England published under section 41 of the Natural Environment and Rural Communities (NERC) Act 2006 (*c*.150 species, to be referred to as NERC species).

Finally, a very detailed exploratory analysis was undertaken of the factors that affect each species, based on detailed information of each species' ecology, and in the regions for each species of contraction, stability and expansion. This tested the Oliver *et al.* (2012) framework which aims to identify potential conservation adaptation actions in a systematic way. Given that this is a relatively detailed analysis, it was only feasible for a subset of 30 representative species. The results of this assessment was framed within the context of the *Making Space for Nature* report of Lawton *et al.* (2010) and its suggestion that the development of a coherent ecological network in England should focus on making sites "better" in quality, "bigger" in size, "more" through adding sites where there are gaps in the network and "joined", through facilitating connections to encourage movements of plants and animals between sites.

Next steps

The overall aim of this project is to provide information to help inform action on the ground, to assist with the prioritisation of actions for species of conservation concern and to help guide Natural England's response to the challenge of climate change. A user's guide to the results is provided at the end of this section.

However, this project should not be seen in isolation. Natural England has been facilitating and undertaking a suite of research projects and the development of tools to help practical conservation action on the ground. Associated projects include:

- Testing the effectiveness of climate change adaptation principles for biodiversity conservation (Oliver *et al*. 2013).
- The role of landscape and site scale characteristics in making species populations resilient to climate change and extreme events (Oliver *et al*. in press).
- The developing of a National Biodiversity Climate Change Vulnerability Model – a tool to help identify areas of higher or lower vulnerability in England (Taylor *et al.* 2014).
- Research to identify potential "refugia" for species against climatic change (Suggitt *et al*. 2014)
- Research to identify how landscape features may help increase the resilience of species to climatic shocks (Newson *et al.* 2014).
- Research on understanding the concept and conservation practice of ecological resilience (Morecroft *et al.* 2012).
- Research on the potential impacts of climatic change on the designated features of protected sites (Johnston *et al.* 2013).

We have recently published (with RSPB, Environment Agency and Forestry Commission) the first edition of a *Climate Change Adaptation Manual* (Natural England & RSPB 2014) that brings together much of our present knowledge about conservation management in a changing climate. We plan to update this with more species information and the project reported here will be an important input to this. The updated manual will provide detailed examples of how conservation managers can use information in the current report, building on the outline provided below.

A brief (cautionary) guide to using the results from this report

"Prediction is very difficult, especially if it's about the future."

--Nils Bohr, Nobel laureate in Physics

This report provides a wealth of analyses and detail concerning the potential and projected changes in the distributions of over 3000 species in England. For Natural England staff and others, there is the natural inclination to want to use the results to help understand how individual species on "their" patch might be affected by climate change and which species might become new colonists. We provide some notes, below, to help people to undertake their own exploration of the results. Natural England climate change specialists are always willing to provide support and advice and welcome feedback.

Some brief cautionary notes
Before describing what sort of information can be found we would like to **stress the following:**

- While this project has used the current state of the art with regard to climate modelling of species distributions, **these are projections**. i.e. *they are not predictions of what will happen*. It is best to consider them as giving an *indication* of the likely direction of change – but there are many other factors that can affect species distributions and which are not built into these models – not least, the influence of human land management and landuse – so species may not be able to colonise areas as readily as suggested or may survive in an area despite the likelihood of the climatic changes that would appear to make an area unsuitable in the future.
- **The projections are associated with many uncertainties**, which is another reason for viewing them with a certain degree of caution. A list of issues concerning climate envelope modelling is given briefly above and further detail can be found in the report. The climate projections that are used are also associated with some uncertainty and the data on current and historic distributions of wildlife also have errors associated with them for a variety of reasons. However, these issues have been considered carefully and controlled using the best analytical techniques, although they still need to be born in mind when interpreting the results.
- **Whether a species might be able to colonise an area depends on many factors**, not least of which is the species' dispersal ability, but also how connected are the source populations to a potential new site; whether the habitat and soil characteristics are suitable: and whether there are potential competitors in the new site that might reduce the success of a colonisation attempt.
- **Species may persist in areas that are potentially unsuitable** for a variety of reasons. In some cases there may be a long lag between conditions becoming unsuitable and species actually disappearing (for example many plants may survive for decades but be unable to reproduce); in other cases there may be features of the environment that mean that it remains suitable (e.g. through lack of competitors), despite change in the climate; in other cases there may be smaller sub-areas within a larger area that maintain a suitable climatic conditions because of factors, such as landscape features, that promote wet or cool conditions.
- **The analyses are "broad-brush"** – due to the numbers of species involved, general analytical approaches have been used to analyse all the species in the same way. Whilst we think that the approach is good for many of the species covered, there may be some that, due to our ignorance of their ecological requirements, may not be adequately analysed. Thus the results for individual species need to be looked at carefully with regard to available information on species ecology.

However, these analyses still have value despite the inherent uncertainties mentioned above. The analyses presented in this report have attempted to control or quantify the uncertainties, using some of the most effective recently developed methods. Furthermore the data available for England is probably the best that can be found anywhere in the world, due to the long tradition of expert naturalists teaming up with professional scientists to help design, collate, validate and analyse surveillance data. **Thus the report represents the best information of this sort currently available to help guide conservation managers**

in how to prepare for some of the impacts of climate change in England. The users just need to be aware that, like most such information, it needs to be used carefully and in conjunction with other sources of information, place-based knowledge and knowledge of the ecological requirements of particular species.

A step-by-step way to explore the results

This assumes that somebody wants to review the likely impact of climate change on key species of conservation interest in a specific area.

(a) **<u>Basic framework results</u>** – this analysis covers *c.*3000 species and assesses where climatic conditions suitable for a species are likely to be found as a result of 2° or 4° global warming up to about the year 2100, but doesn't take into account other environmental factors (these are included in the full framework results below):

- Look up the species in either the 2° or 4° worksheets in *Basic framework results.xls*. (a screen shot is below).

	A	B	C	D	E	F	G	H	I	J	K
1	Group	Latin name	English name	NERC priority?	Observed decline	Projected decline	Risk of decline	Observed expansion	Projected expansion	Benefit from expansion	Final outcome
22	Bees	*Andrena bucephala*	NA	0	> -1%	> -1%	LOW	+4 to +7.5%	> +7.5%	VERY HIGH	High benefit
23	Bees	*Andrena chrysosceles*	NA	0	-4 to -1%	-7.5 to -4%	HIGH	> +7.5%	< +1%	MODERATE	Medium risk
24	Bees	*Andrena cineraria*	Grey Mining Bee	0	< -7.5%	-7.5 to -4%	VERY HIGH	> +7.5%	< +1%	MODERATE	High risk
25	Bees	*Andrena coitana*	NA	0	< -7.5%	< -7.5%	VERY HIGH	> +7.5%	< +1%	MODERATE	High risk
26	Bees	*Andrena congruens*	NA	0	< -7.5%	> -1%	MODERATE	> +7.5%	> +7.5%	VERY HIGH	High benefit
27	Bees	*Andrena denticulata*	NA	0	< -7.5%	> -1%	MODERATE	+4 to +7.5%	> +7.5%	VERY HIGH	High benefit
28	Bees	*Andrena dorsata*	NA	0	> -1%	< -7.5%	MODERATE	> +7.5%	< +1%	MODERATE	Risks & benefits

- For each species there are three columns that show information to do with the historical range of that species (reddish colour; for most taxa this is the distribution recorded between 1970-1989, but see text for more details); and three for changes outside this range (coloured blue on the spreadsheet).
- For the existing range (columns E to G in the spreadsheet): there are measures of the rate of decline in populations per decade (expressed as a percentage) measured up to present, then rates of projected decadal decline up to 2100. Thus, for example, The grey mining bee has declined more than 7.5% per decade, and is likely to decline by between 4 and 7.5% per decade up to the year 2100. The next column (G) is a summary that compares the projected decline with current decline, for the grey mining bee, this is assessed as "very high". A mismatch between the two tends to *reduce* the assessed risk, as shown in the table below, which is Table 1.2 in the main report:

Observed\Projected Decrease	**>7.5 %**	**4.0 – 7.5 %**	**1.0 – 4.0 %**	**< 1.0 %**
>7.5 %	VERY HIGH	VERY HIGH	HIGH	MEDIUM
4.0 – 7.5 %	VERY HIGH	HIGH	HIGH	MEDIUM
1.0 – 4.0 %	HIGH	HIGH	MEDIUM	MEDIUM
< 1.0 %	MEDIUM	MEDIUM	MEDIUM	LOW

- For the projected range (columns H to J on the spreadsheet): there are measures of the decadal population increase measured up to present, then rates of projected decadal increase up to 2100. Again, for the grey mining bee, it has expanded outside its historical range by more than 7.5% per decade, but it is not projected to show much expansion due to climate change, , at less than 1% per decade. Column J provides a summary measure of the opportunity due to climate change which compares the projected increase with current increase. For the grey mining bee, it is only likely to have a moderate benefit from climate change. A mismatch between the two, tends to reduce the likely opportunity, as shown in the table below, which Table 1.3 in the main report:

Observed\Projected Increase	>7.5 %	4.0 – 7.5 %	1.0 – 4.0 %	< 1.0 %
>7.5 %	VERY HIGH	VERY HIGH	HIGH	MEDIUM
4.0 – 7.5 %	VERY HIGH	HIGH	HIGH	MEDIUM
1.0 – 4.0 %	HIGH	HIGH	MEDIUM	MEDIUM
< 1.0 %	MEDIUM	MEDIUM	MEDIUM	LOW

- The assessments of risks and opportunities in current and new ranges are then brought together to provide an overall assessment for each species (column K in the spreadsheet), reported in the last column of the spreadsheet. The classification of overall impact is described in the table below, which is Table 1.4 in the main report:

Opportunity\ Risk	VERY HIGH	HIGH	MEDIUM	LOW
LOW	HIGH RISK	HIGH RISK	MEDIUM RISK	LIMITED IMPACT
MEDIUM	HIGH RISK	MEDIUM RISK	RISKS & & OPPORTUNITY	MEDIUM OPPORTUNITY
HIGH	MEDIUM RISK	RISKS & & OPPORTUNITY	MEDIUM OPPORTUNITY	HIGH OPPORTUNITY
VERY HIGH	RISKS & & OPPORTUNITY	MEDIUM OPPORTUNITY	HIGH OPPORTUNITY	HIGH OPPORTUNITY

Thus, for the grey mining bee, a very high risk in its existing range combined with only a medium opportunity in the area beyond this range, results in a overall assessment of a high risk posed by climate change.

(b) Full framework results – this analysis covers 400 species, including 155 that are priority species listed under the NERC Act. The analysis was more time consuming and takes into account other knowledge about a species' trends and other factors that may affect a species, and how it responds to climate change. Thus, if previous studies, have shown a good link between population change and climate change, then the confidence in the projected changes associated with climate change is increased; if there is good evidence for other factors having driven a decline, then the likely effect of climate change is down-graded. Similarly, if there are factors that might make a species more vulnerable to climate change, such as restricted range or restricted habitat use, then the potential impact of climate change was upgraded. **The key aspect of the full framework results is that they tend to suggest that species are likely to suffer more from climate change than indicated by the basic framework.**

- Look up the species of interest in either 2° or 4° worksheets in *Full framework results.xls*.
- The lay out is similar to the basic framework, as described above and uses the same classifications of risk and opportunities. Changes in the historical range are in columns E to H; changes outside the historical range in columns I to L; the overall assessment of risk and opportunity is in Column M.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Group	Latin Name	English name	NERC priority species?	Observed decline	Projected decline	Risk of decline	Associated confidence	Observed expansion	Projected expansion	Benefit from expansion	Associated confidence	Final outcome
35	Birds	*Alauda arvensis*	Skylark	Y	-4 to -1%	> -1%	LOW	MEDIUM	+1 to +4%	< +1%	LOW	LOW	Limited impact
36	Birds	*Anas platyrhynchos*	Mallard	N	> -1%	> -1%	LOW	MEDIUM	+1 to +4%	< +1%	LOW	LOW	Limited impact
37	Birds	*Anthus trivialis*	Tree Pipit	Y	< -7.5%	-7.5 to -4%	VERY HIGH	LOW	+1 to +4%	< +1%	LOW	LOW	High risk
38	Birds	*Asio flammeus*	Short-eared Owl	N	< -7.5%	-7.5 to -4%	VERY HIGH	MEDIUM	> +7.5%	< +1%	LOW	LOW	High risk
39	Birds	*Botaurus stellaris*	Bittern	Y	< -7.5%	> -1%	LOW	LOW	> +7.5%	> +7.5%	HIGH	MEDIUM	High benefit
40	Birds	*Branta canadensis*	Canada Goose	N	> -1%	-7.5 to -4%	MODERATE	LOW	> +7.5%	< +1%	LOW	LOW	Medium risk
41	Birds	*Branta leucopsis*	Barnacle Goose	N	< -7.5%	-7.5 to -4%	VERY HIGH	MEDIUM	> +7.5%	> +7.5%	VERY HIGH	MEDIUM	Risks & benefits
42	Birds	*Burhinus oedicnemus*	Stone-curlew	Y	< -7.5%	-4 to -1%	VERY HIGH	MEDIUM	> +7.5%	> +7.5%	HIGH	LOW	Medium risk
43	Birds	*Buteo buteo*	Buzzard	N	> -1%	-4 to -1%	LOW	LOW	> +7.5%	< +1%	LOW	LOW	Limited impact

(c) <u>Final note</u> – the interpretation of the results for any particular location depends on where that location is with respect to a species' distribution. As might be expected, there are thousands of maps that also need to be consulted to understand these results fully. It is intended to make these maps available in due course.

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Introduction

Globally, climate change poses a serious threat to the long-term persistence of many species (Thomas *et al.* 2004, Jetz *et al.* 2007, Bellard *et al.* 2012). There is increasing evidence that species distributions are shifting (Hickling *et al.* 2006, Chen *et al.* 2011) and ecological communities changing (Davey *et al.* 2011, Devictor *et al.* 2012) in response to recent warming. The evidence was recently reviewed for the UK (Morecroft & Speakman 2013). As a result of these concerns, there is an urgent need for conservation organisations and agencies to adapt their action in response to the threat of climate change (Heller & Zavaleta 2009, Hodgson *et al.* 2009, Green & Pearce-Higgins 2010). From an English and UK perspective, a number of key general principles for adaptation action have been identified (e.g. Hopkins *et al.* 2007, Smithers *et al.* 2008), which include making sound decisions based on analysis and strategic planning. An important component of such adaptation, which until recently has been largely neglected (Heller & Zavaleta 2009), is that of species prioritisation. Once this has been established, both at the species level, and for populations within individual countries and regions, then appropriate adaptation measures can be identified for those populations (e.g. Oliver *et al.* 2012). This report addresses both topics.

Firstly, in order to target conservation resources efficiently and effectively, the robust and justifiable prioritisation of species for conservation action is needed. This should include a consideration of the likely vulnerability of some species to climate change, balanced against the potential opportunity that climate change may provide to other species. The first chapter of this report considers an assessment of risks and opportunities that species in England will face as a result of climate change based on the outputs of bioclimate models that project future changes in species' distributions in response to climate change. We do so for over 3,000 species, making this the most comprehensive assessment of the likely impact of climate change on the biodiversity of a country anywhere in the world. In the second chapter, we apply these methods to future projections of changes in populations of Annex I and migratory bird species within the UK, building on the results of the CHAINSPAN project which used bioclimate models to predict the impact of climate change on species' abundance, rather than just distribution (Pearce-Higgins *et al.* 2011).

Secondly, it is important to consider the potential implications of these priorities for the adaptation of conservation action on the ground to climate change. This is done in Chapter 3, building on the results in Chapter 2, to consider how land management for birds in the UK may need to be adapted in response to climate change. Finally, in Chapter 4, we consider for a subset of non-avian species from Chapter 1, how the conservation actions they require may need to be adapted and adjusted in the light of climate change.

1 Assessment of risks and opportunities for a wide range of species in England

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Introduction

There is already a standardised approach for international, national and local bodies with an interest in nature conservation to use information about threats to species and habitats to prioritise those in greatest need of conservation action (Mace *et al.* 2008; Eaton *et al.* 2009). This is largely based on historical and recent trends and threats, and does not generally consider the likely long-term future threat of climate change. A number of different approaches have been developed in order to help conservation organisations incorporate the potential impacts of climate change when considering conservation priorities (e.g. Thomas *et al.* 2011, Gardali *et al.* 2012), as organisations have realised the importance of appropriate targeting of limited conservation resources in a changing climate. In this project, we have applied one of these approaches, that of Thomas *et al.* (2011), to a wide range of plant and animal species in England, in order to assess the risks and opportunities that climate change poses to those species. This framework combines information on observed population or distribution changes with projected future changes in order to generate separate measures of expected decline and increase, with associated confidence, and is summarised in Figure 1.1 (further details are provided below and in Appendix 6).

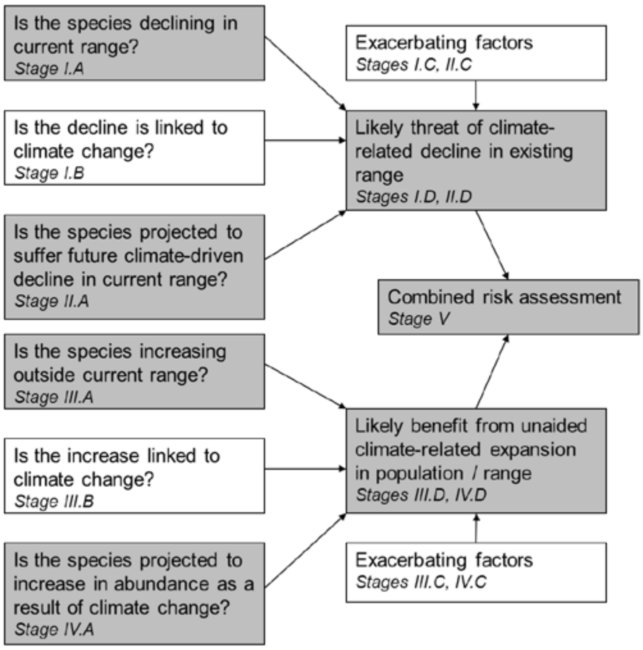

Figure 1.1 Summary of the processes involved in the application of the full Thomas *et al.* (2011) framework, and how those are represented by the various stages of the process. Those boxes in grey represent the information used in the basic framework.

In brief, the frameworks assess the current and projected changes in the distribution of a species in both its historical range and outside its historical range. They thus suggest whether a species is likely to be threatened by climate change in its historical range and whether a species is likely to spread into new areas with climate change. The difference between basic and full frameworks is that the latter uses more detailed knowledge about the likely causes behind current changes in distribution, and whether a species is more vulnerable to environmental perturbations due to factors such as a very small current range or ecological constraints due to habitat limitations.

In most cases, projected changes are likely to be derived from bioclimate modelling, in which spatial variation in the distribution of a species is modelled as a function of climate. Potential future changes in climate suitability for that species are then derived by applying that model to projections of future climate (e.g. Huntley *et al.* 2007). Assuming that the species tracks the change in climate perfectly, these changes in suitability may be inferred to reflect likely changes in range extent. This is unlikely to be a valid assumption, given dispersal limitation of species (e.g. Barbet-Massin *et al.* 2012) and the role of other non-climatic factors (e.g. soil, habitat) in defining realised range, so it is important to recognise that these projections are simply indications of *potential* range change. This technique can be widely applied to any species with distribution data, leading to large-scale assessments of species vulnerability or extinction risk in response to climate change (e.g. Thomas *et al.* 2004, Bellard *et al.* 2012, Warren *et al.* 2013), as well as the first cross-taxa assessment for the UK: the MONARCH project (Walmsley *et al.* 2007). Bioclimate modelling studies have been subject to criticism as a result of the assumptions involved (e.g. Beale *et al.* 2008). In this study, we use a novel method that deals with some of these shortcomings (Beale *et al.* 2014). The method used addresses the problem of spatial autocorrelation in large-scale species' distribution data that could lead to the mis-estimation of occurrence-climate relationships by fitting flexible relationships between occurrence and climate change whilst accounting for the relative proximity of different locations to each other. Although for each species the model is constructed using distribution data from Great Britain, by adopting a Bayesian approach, it is possible to also incorporate equivalent data from Europe within the same analytical framework, thus enabling better assessments of species' responses to future climates not currently found within the UK.

Methods

The application of the framework involves a number of steps. First, distribution data were collated for a wide range of taxa that occur in England (Table 1.1), including invertebrate data and plant data which are collated, managed or accessed by the Biological Records Centre (BRC) on behalf of national recording schemes and societies (Table 1.1). Hereafter, we refer to these data simply as 'BRC datasets', but much of these data are also available from the NBN gateway (http://data.nbn.org.uk/). Bird data were from the British Trust for Ornithology (BTO). Second, statistical models linking species' distributions to climate were produced, and then used to assess the likely impacts of future climate change upon species potential distributions.

Table 1.1 Summary of the coverage of different species groups by this risk assessment

Taxon	Recording Scheme	Link	Total species with distribution data	Species for which climate models converged[2]	Species for which trends could be calculated	NERC priority species with effort corrected
Native vascular plants	Botanical Society of the British Isles (BSBI)	www.bsbi.org.uk	1,365	1,339[1]	852	38
Bryophytes	British Bryological Society	www.britishbryologicalsociety.org.uk	1,049	850	520	1
Moths[2]	Butterfly Conservation	www.mothscount.org/text/27/national_moth_recording_scheme.html	668	622	422	58
Spiders	British Arachnological Society, Spider Recording Scheme	www.BritishSpiders.org.uk/	512	374	297	7
Coleoptera-Carabids	Ground Beetle Recording Scheme	-	317	266	175	3
Diptera-Hoverflies	Dipterists Forum, Hoverfly Recording Scheme	www.hoverfly.org.uk/	249	213	175	0
Bees	Bees, Wasps and Ants Recording Society (BWARS)	www.bwars.com/	225	187	143	6
Wasps	Bees, Wasps and Ants Recording Society (BWARS)	www.bwars.com/	219	161	133	1
Birds	British Trust for Ornithology	www.bto.org/	180	180[3]	180	41
Centipedes & Millipedes	British Myriapod and Isopod Group, Centipede Recording Scheme	groups.google.com/group/bmigroup/web/index-2	85	66	39	0
Diptera-Craneflies	Dipterists Forum, Cranefly Recording Scheme	www.dipteristsforum.org.uk	78	64	11	0

Coleoptera- Soldier Beetles and allies	Soldier Beetles, Jewel Beetles and Glow-worms Recording Scheme	-	53	46	22	0
Coleoptera- Cerambycid Beetles	Cerambycidae Recording Scheme	-	52	40	0	0
Dragonflies & Damselflies	British Dragonfly Society, Dragonfly Recording Network	www.dragonflysoc.org.uk/	45	35	26	0
Coleoptera- Coccinnelids	Ladybird Recording Scheme	www.ladybird-survey.org	44	38	17	0
Grasshoppers & Crickets	Orthoptera Recording Scheme	www.orthoptera.org.uk	43	31	23	0
Ants	Bees, Wasps and Ants Recording Society (BWARS)	www.bwars.com/	36	28	13	0
TOTAL			**5,220**	**4,540**	**3,048**	**155**

[1]For 354 of these, European data were also available.

[2] Butterflies were already covered at a UK scale by Thomas *et al.* (2011) and so are not considered further.

[3]Models for two species failed to converge when built using only UK data.

[4]For a subset of species, it was not possible to generate robust models linking their occurrence to climate. These were excluded from the risk assessment process.

These projections were then compared to observed recent range changes, in order to assess the risk and opportunities faced by each species in a changing climate using a basic framework that was based on Thomas *et al.* (2011), but did not consider potential confounding and exacerbating factors (Figure 1.1). This assumes that species which have showed little evidence of range contraction, or range expansion in response to recent climate change, are less likely to be at risk of future range contraction, or realise the potential opportunity associated with future range expansion, than those which are already responding as expected.

Finally, for a subset of 400 species, a more comprehensive assessment, based on the full Thomas *et al.* (2011) framework, was completed. These included all species for which data and models were available, that are listed as of principal importance for the conservation of biodiversity in England in section 41 of the Natural Environment and Rural Communities Act (hereafter referred to as NERC species). These were balanced by a random selection of non-priority species across taxa, by way of comparison. For these 400 species, additional ecological information on the evidence linking population / range changes and climate, and on potential exacerbating factors (e.g. range extent and population size, ecological constraints associated with habitat-availability, dispersal and inter-specific interactions) was used to identify relevant factors that might moderate or exacerbate the risk/opportunity to each species from climate change,. Species were ultimately scored on the basis of the likelihood of climate-related decline and climate-related expansion occurring in the future, with an assessment of confidence. The basic framework therefore delivered a list of species likely to be at high risk of climate-related decline and species likely to face opportunity from climate change for all species but based only on projected and observed distribution changes. The full framework was applied to a subset of species, but included consideration of additional ecological information and gave a measure of confidence associated with each assessment.

Each of these steps is elaborated on below.

Bioclimate modelling

There is significant variation in the outputs from climate envelope models, depending on the modelling method used and emission scenario and GCM (General Circulation Model) applied (Diniz-Filho *et al.* 2009, Buisson *et al.* 2010). We therefore used a standardised climate envelope model across all taxa in order to ensure that cross-taxonomic comparisons were fair and unbiased by the methods used. There were taxonomic differences in data availability and quality, which we attempted to account for, but that may still affect the interpretation of our results. European distribution data were available for birds and plants only. Therefore, for these groups, future projections of change are likely to be more robust (see Appendix 3). Distribution data from Great Britain were based on structured repeat atlas data for birds with comprehensive coverage at the hectad (10km) scale. For other taxa, recording coverage 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. Coverage is best for well developed, popular recording schemes such as vascular plants, bryophyte and butterflies, which have very good coverage at hectad scale, whilst other schemes for less popular taxa have poorer coverage. Therefore standardisation of survey data is necessary in the analysis of these data. Therefore we used the program FRESCALO (Hill, 2011) to produce estimates of recorder effort for each 10km square for each of the 17 taxonomic groups studied (Appendix 1). FRESCALO assesses recorder effort by comparing observed species to those expected from nearby neighbourhoods that have 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. To identify any artefacts introduced by using observer effort models we modelled the bird dataset (where observer bias is considered lowest) using simple models and using occupancy models to account for observer effort, expecting the two sets of models to be essentially identical. There was indeed a strong correlation between estimated range changes derived from the simple models and the observer models, with the observer model marginally reducing the magnitude of change expected. Given that analyses of the BRC dataset supported the need to account for observer effort for other taxa, it is clear that occupancy models should be used whenever observation effort can be estimated. Any potential biases introduced by using the more complicated model are far smaller than the problems caused by not accounting for observer effort (Appendix 1).

Four bioclimate variables were used to describe spatial variation in the climate using 1961-1990 averages:

- mean temperature of the coldest month (MTCO): a measure of winter cold
- growing degree days (GDD5): a measure of the plant growth season
- the coefficient of variation of temperature (cvTemp): a measure of seasonality
- soil moisture (soilWater): a measure of moisture availability

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.

For models at the British scale, observed climate data, on a 5 km × 5 km grid, from the period 1961-90 were downloaded from the UK Met Office (http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/). These were taken to represent the baseline climate that would be used to describe observed species distributions. Climate change data were downloaded from the UKCP09 user interface (http://ukclimateprojections-ui.defra.gov.uk). To ensure that climate data were consistent across adjacent grid cells and to ensure that different climate variables were consistent within the same grid cell, we used the Spatially Coherent Projections (probabilistic projections, the generally preferred UKCIP09 product, are conditioned on global temperature changes and are not spatially consistent between cells (hence should not be used for spatially explicit modelling) and are not consistent between variables within the same cell (e.g. it is obvious that the 95th percentile of rainfall need not co-occur in any one reasonable climate scenario with the 95th percentile of temperature)). To represent UK climate under global temperature changes of 2°C and 4°C with the spatially coherent projections, the same combinations of time period and SRES scenario as were used to produce the global-temperature-change products were selected: 2070-99 for scenario B1 (2°C change) and 2070-99 for scenario A1B (4°C change) (http://ukclimateprojections.defra.gov.uk/22614). As the spatially-coherent projections have data from 11 RCM ensemble members, to which no probability or certainty is attached, all 11 ensemble members were used to generate projections, giving 22 future climate datasets in total.

We extracted mean temperature (°C), cloud cover (%) and total rainfall (mm) on a monthly timescale. Observed data were aggregated to a 10 km × 10 km grid using the mean value. Climate change data were provided at an approximate 25 km resolution, but represented a 25 km resolution change value. Change values were applied to the underlying 5 km resolution observed data. Averages of the resulting surfaces were then calculated at 10 km resolution. The resultant maps gave absolute values for each climate variable in the future scenarios at the required resolution.

For European-scale models, observed climate data from the period 1961-90 were acquired from the Tyndall Centre for Climate Change Research; dataset CRU TS 1.2. These data were aggregated using means to the 50 km UTM grid as used in the *Atlas Florae Europaeae* (http://www.luomus.fi/en/atlas-florae-europaeae-afe-distribution-vascular-plants-europe). As with UK climate data, we used mean temperature, cloud cover and total rainfall on a monthly timescale. Raw climate data were converted into appropriate bioclimatic variables that should have more direct influences on species' distributions in the same way as described above for UK climate.

Distribution data, primarily from 1970-89, were used to determine species distribution. This time period was used because, with an increasing magnitude of climate change being recorded after this period, more recent distributions may be increasingly out-of-step with the climate (further details of the distribution data used are provided in Appendix 2). Native vascular plants and birds were slight exceptions. For plants, in order to be consistent with the start and end date of major Atlases, we used the period 1970-86. For birds, the first survey period spanned 1988-91, again for consistency with a breeding bird atlas (Gibbons *et al.* 1993). A total of seventeen taxonomic groups were covered in the analysis. Species occurrence data were obtained from the Biological Records Centre or directly from the scheme or society that collected the data (Table 1.1). These data contain records of where and when species have been observed. Within each group, the species selected were present in England and recorded on more than 5 squares of 10 x 10 km in Great Britain (following Hickling *et al.* 2006 to ensure there was a minimum amount of data for modelling). In total, this yielded 5,280 species. However, for some very sparsely distributed species, models failed to converge (see below), giving a total of 4,540 species for which bioclimate envelope models were produced (Table 1.1).

The method used for the bioclimate modelling was devised by Beale *et al.* (2014) in order to address the problem of spatial autocorrelation in large-scale species' distribution data (Beale *et al.* 2008). We applied a Bayesian, spatially explicit (Conditional Autoregressive) Generalised Additive Model to species' distribution data in order to separate climatic, spatial and random components in determining the distribution of each species. This approach accounts for potential spatial autocorrelation in the data (one of the main criticisms of Beale *et al.* 2008 that may lead to false or inaccurate relationships between occurrence and climate), and fits flexible relationships between species' occurrence and the climate data. For those taxa for which European data were available, models were initially constructed using uninformative priors (i.e. we have no prior knowledge of what this relationship should be) across Europe to describe the relationship between occurrence and climate. Once converged, a second model was fitted to the finer-scale distribution data from Great Britain using informative priors from the European-scale analysis. As a result, any strong climatic signal based on the European distribution would remain essentially unchanged when modelled using British data only, unless the evidence for a different climatic signal within the UK is strong. In cases where there was uncertainty in the estimation of species' responses at a European level, then the British model would be more heavily informed by outputs from the British component of the model (Figure 1.2). For species for which data from Great Britain only were available, only the second model was conducted but using uninformative priors rather than priors based upon information from the European distribution. In order to assess the potential limitations of this approach for species for which British data only were available, we produced models for plants and birds using both European and British data, and British-only data, and compared the outputs (Appendix 3). When defined from the combinations of four bioclimate variables within the current UK climate, projections of future British climate by 2070-99 under both low (2˚ scenario) and medium (4˚ scenario; explained below) were largely outside of the range of observed combinations. Thus, most places in Britain are projected to experience climate that is not the same as climate that is currently experienced in the country. However, for most places, these climates did match the climate that is currently found in a part of Europe. Novel climates across most of Britain increase the uncertainty associated with future projections, especially when based only on British data. In particular we found a tendency for Britain only models to generate more extreme results and, therefore, our assessments for taxa other than birds and plants may tend towards an overestimation of change (both positive and negative). This is because they don't fully capture the potential climate space of species because climatically suitable areas that they occupy in Europe do not contribute to the construction of their models. Nevertheless when interpreted carefully they should still be informative as to which species are at greatest relative risk from climate change, or most likely to expand their range in the country.

Future projections of climate change were based on UKCP09 projections for 2070-2099 for B1 and A1B models, equivalent to approximately 2°C vs. 4°C scenarios of global warming (See Figure 1.3 for an example). This comparison enables an assessment of likely impacts of an increasing magnitude of climate change upon species in the UK to be made (Appendix 4). These results show that species impacted by a 2˚ global warming scenario are even more impacted by the 4˚ scenario (as measured by changes in the number of 10 x 10km squares each species was projected to occupy), with almost perfect correlation between the results. However, the difference between the two scenarios appears small, relative to the changes projected to occur between the current climate and both future projections. This appears to be because the two global scenarios produce smaller differences locally within the UK, with most changes having already occurred under a global 2 ˚change scenario, according to the scenarios we used.

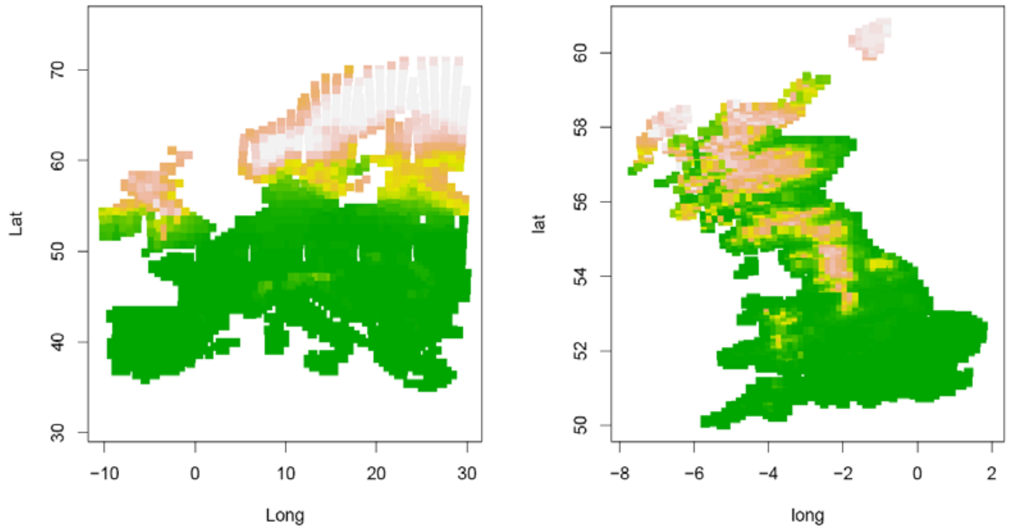

Figure 1.2 Modelled occurrence of golden plover *Pluvialis apricaria* at the European scale based on European distribution data (left) and Great British scale based on British data, but with climatic relationships informed by relationships across Europe (right). Pale colours indicate increasing probability of occurrence.

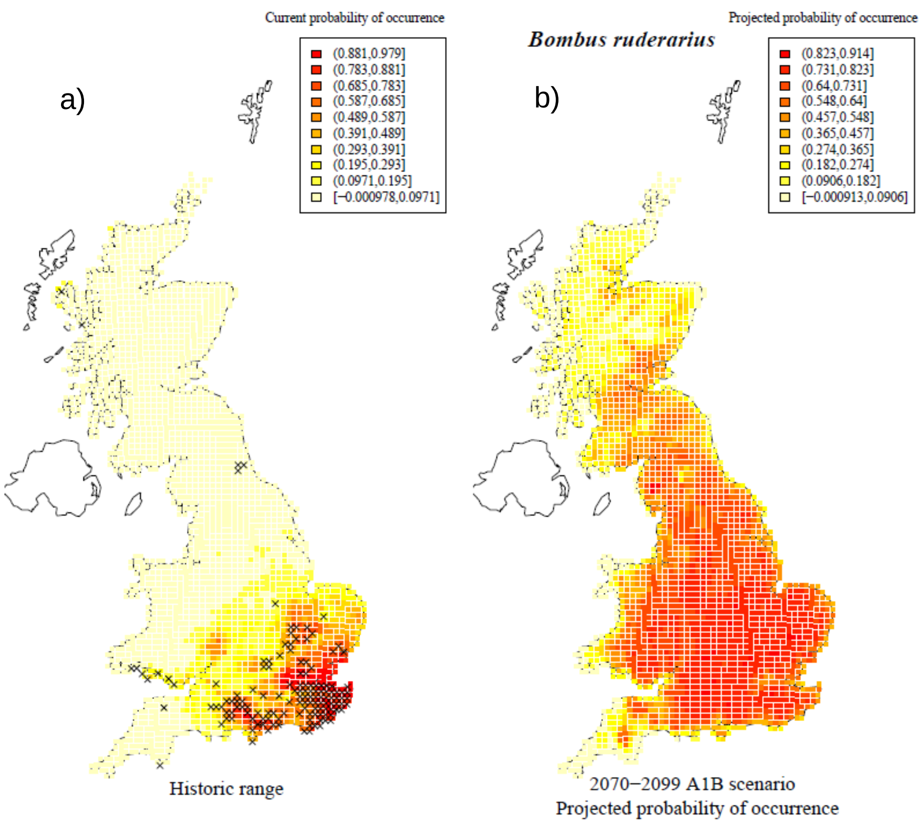

Figure 1.3 Maps showing a) historic distribution of an example species, *Bombus ruderarius.* Black crosses show submitted records, coloured squares show modelled probability of historic (1970-1990) occurrence; b) Projected probability of occurrence under a medium A1B scenario.

Trend estimation
Existing population monitoring and distributional data from a range of different national schemes were used to identify range changes within both the recent occupied historical distribution (for most taxonomic groups defined by the distribution of a species from 1970 to 1989, and subsequently referred to as the historic range), and outside the historic range, in order to identify potential colonisation of new areas in response to climate change that occurred from 1990 (referred to as the current range). For birds, range changes were simply derived from a comparison of the distribution from the 1989/91 breeding bird atlas to the 2007/11 breeding atlas, on the basis of the number of 10 km squares with confirmed breeding evidence. For plants, the historic baseline was 1970 to 1986, to match the data of the first plant atlas. For remaining taxa, distributional changes required correction to account for variation in observer effort. This was corrected for, using the approaches of Hill (2011) and Roy *et al.* (2012).

Range contractions were measured using data from 1970 to 2009 using mixed-effects models (Roy *et al.* 2012), incorporating years describing both the historic and current range, in order to document change. To account for incidental records from poorly sampled squares, which might erroneously appear to be colonisations, we restricted data to 'well-sampled' combinations of 1 km square and date (a visit), defined as occasions when the number of species recorded in a particular taxonomic group was greater than or equal to 4. Additionally, 1 km squares were included only if they were well sampled on three or more visits and were within the historic range. These filtered data were used in a mixed effects model where site was included as a random effect and year as a fixed effect. The resulting trend estimate was converted into a percentage decadal change.

To assess colonisation outside the historic range, data were analysed at the 10 km square resolution. To control for recorder effort in this analysis we used the program FRESCALO (Hill 2011). We calculated recorder effort as the proportion of species observed in a 10km square (hectad) relative to the total number of species expected. We selected a threshold of recorder effort of 0.25 to define an 'adequately sampled' square, but used higher thresholds of 0.5 and 0.75 to assess confidence in these results (i.e. confidence was higher if expansion rate categories were the same using the stricter, more conservative criteria). The number of colonised hectads was calculated as the number of hectads outside the historic home range occupied in the second time period that were not occupied in the first time period, considering only hectads that were 'adequately sampled' in both time periods. This was then divided by the number of 'adequately sampled' hectads within the home range, occupied in the first time period. This percentage was then converted to a decadal value.

Basic framework
To ensure that results were obtainable for all species groups, a simplified version of the Thomas *et al.* (2011) framework was applied to all taxa, based on projected changes in future distribution compared with observed recent changes in distribution only (Figure 1.1). This did not therefore include consideration of the extent to which observed changes may have been caused by non-climatic factors, or an assessment of exacerbating factors which may moderate or enhance species' responses to climate change, and only used the information from part A of Tables 1 to 4 of Thomas *et al.* (2011). As a result, the outputs from this basic framework may conflate the risk of climate change with declines and range contractions for non-climatic reasons. For example, a species with a 7.5 % per decade

decline in range extent for a reason unrelated to climate change will be classified as being at least of medium risk of negative climate change impact (Table 1.2). Thus, the outputs from this basic framework may over-emphasise the likely rate of future change as a result of climate change.

To produce the basic framework, current trends within the historic range were compared against the magnitude of projected contraction in potential range in order to assess risk (Table 1.2). Similarly, any expansion of the current range outside of the historic range was cross-tabulated against the magnitude of projected future range expansion outside the recent range (Table 1.3), thus matching the first elements of the assessment in the Thomas framework. The outputs from the two tables in turn were cross-tabulated to provide an overall assessment of species' risks and opportunities (Table 1.4). If a species has failed to respond in the way expected to the climate change that has already occurred, this could either be because of error in the model projections, or lags in the species' response. In order to be conservative, this approach reduces the magnitude of any likely climate change threat or opportunity in cases where recently observed and future projected changes do not match. For species exhibiting long lag-times in response to climate change, this may under-estimate the likely risk or opportunity that they face.

Table 1.2 Cross-tabulation of likely threat to species from climate change based on observed and projected decadal changes in range extent / population size within the current range

Observed\Projected Decrease	**>7.5 %**	**4.0 – 7.5 %**	**1.0 – 4.0 %**	**< 1.0 %**
>7.5 %	VERY HIGH	VERY HIGH	HIGH	MEDIUM
4.0 – 7.5 %	VERY HIGH	HIGH	HIGH	MEDIUM
1.0 – 4.0 %	HIGH	HIGH	MEDIUM	MEDIUM
< 1.0 %	MEDIUM	MEDIUM	MEDIUM	LOW

Table 1.3 Cross-tabulation of likely opportunity for species from climate change based on observed and projected decadal changes in range extent / population size outside the current range

Observed\Projected Increase	**>7.5 %**	**4.0 – 7.5 %**	**1.0 – 4.0 %**	**< 1.0 %**
>7.5 %	VERY HIGH	VERY HIGH	HIGH	MEDIUM
4.0 – 7.5 %	VERY HIGH	HIGH	HIGH	MEDIUM
1.0 – 4.0 %	HIGH	HIGH	MEDIUM	MEDIUM
< 1.0 %	MEDIUM	MEDIUM	MEDIUM	LOW

Table 1.4 Cross-tabulation of the risks (Table 1.2) and opportunities (Table 1.3) associated with climate change for each species, in order to summarise the risks and opportunities for each species

Opportunity\ Risk	**VERY HIGH**	**HIGH**	**MEDIUM**	**LOW**
LOW	HIGH RISK	HIGH RISK	MEDIUM RISK	LIMITED IMPACT
MEDIUM	HIGH RISK	MEDIUM RISK	RISKS & & OPPORTUNITY	MEDIUM OPPORTUNITY
HIGH	MEDIUM RISK	RISKS & & OPPORTUNITY	MEDIUM OPPORTUNITY	HIGH OPPORTUNITY
VERY HIGH	RISKS & & OPPORTUNITY	MEDIUM OPPORTUNITY	HIGH OPPORTUNITY	HIGH OPPORTUNITY

Full framework

A subset of 402 species was run through the full framework as described by Thomas *et al.* (2011), and summarised in Figure 1.1. This included all of the NERC priority species covered by the basic framework (155 species), as well as at least 13 species from each taxonomic group in order to provide as broad an appraisal as possible of English biodiversity. The full framework associates a confidence level with each observed and projected population trend, and weights them accordingly in the final output. This requires the incorporation of additional ecological information on the evidence linking population or range changes and climate, and on potential factors that might exacerbate the detrimental effects of climate change or constrain the ability of species to take advantage of potentially beneficial changes (e.g. range extent and population size, ecological constraints associated with habitat-availability, dispersal and inter-specific interactions). We conducted a literature search for each species using Google Scholar and Web of Science to gather this information, supplemented by additional information from species experts (see Acknowledgements). A number of potential limitations to the approach for particular taxa were highlighted by some of the experts consulted. In particular, concerns were expressed about taxa for which there is limited species coverage, so that the data may not be fully representative, there is variation in recorder coverage in space and time, uncertainty about taxonomy, and lack of assessment of the impacts of climate change on many taxa. These were unsolicited, but are useful to present as part of this report as they raise some issues that should be considered when interpreting these findings, and are given in Appendix 5. Some of these issues are addressed as well as is possible through the analytical framework adopted, that should account for spatial variation in species coverage and recorder effort, whilst for poorly-studied taxa, the level of confidence associated with the assessment will tend to be lower. The confidence associated with ecological information required for some aspects of the framework application, was regarded as good if based upon peer-reviewed literature, in order to provide a robust, but relatively quick assessment of confidence. If it was based on expert knowledge then the expert was asked to assign their confidence in the importance of the factor. Species were run though the framework twice, using the projections for 2 and 4 degree scenarios.

The framework laid out in Thomas *et al*. (2011) consists of four stages requiring information on:

- observed population changes within the current range (Stages I.A to D);
- projected population changes within the current range from bioclimatic models (Stage II.A, C & D);
- observed population changes outside current range (i.e. range expansion, Stage III.A, B & D); and
- projected population changes outside the current range (Stage IV. A, C & D).

The results of these are synthesised into a single table resembling Table 1.4 above. The data used for each of the sections are described below, along with any modifications of the framework presented in the original paper (Thomas *et al.* 2011) that were made.

For Stage I, distribution change data (Stage I.A) were based on Atlas data (for birds) and modelling of BRC records as described in the subsection on trend estimation above, for other taxa. Confidence in all bird trends was assessed as good, based on coverage and effort. For other taxa confidence was assessed as good if the mixed model accounting for recorder effort gave a trend where the upper 80% confidence intervals were in the same impact category as the trend (i.e. we are 80% confident that any observed declines were at least that severe). The linkage between population decline and climate (Stage I.B) was assessed initially by comparison of the direction of observed and projected population declines within the current range. If these were both negative then this was assessed as evidence for a link (with poor confidence), if one was positive and one negative then this was classified as no evidence for a linkage. Any evidence in the published literature describing a relationship between climate and population change was used to upgrade the confidence in this section to good. Exacerbating factors were included in Stage I.C, based on expert opinion and scientific literature, and confidence in these factors was also generally based on expert opinion, although if there was a published study showing an impact of a factor on a species' population then confidence was always assigned as 'good'. The outputs from these stages are then combined in Stage I.D to provide an overall summary of the current impact of climate change in a species' historical range (Very High, High, Moderate or Low) and an associated level of confidence (Good, Medium or Low).

Stage II deals with projected declines within the current range, based on bioclimatic models. The confidence in these projections was based on the mean of confidence intervals (corrected for the binomial variance) of the projections across sites, and on a comparison between observed and projected distribution trends. Confidence was assigned as 'high' where the confidence intervals on bioclimatic models (median confidence interval across squares divided by the variance) were greater than a threshold value of 0.02 (selected from a visual assessment of the spread of values) and where current distribution trends were in the same direction as projected trends. Confidence was assigned as medium if the confidence interval threshold was met but projected and observed trends were in opposing directions, and low if the median weighted confidence interval was >0.02. The outputs from these stages are then combined in Stage II.D to provide an overall summary of the likely impact of future climate change in a species' historical range (Very High, High, Moderate or Low) and an associated level of confidence (Good, Medium or Low).

Stage III.A and III.B were completed as for Stages I.A and 1.B, using information about distribution increases outside current range. The only difference was that, as described in Thomas *et al.* (2011), decadal population increases in section III. A were calculated relative to the species' status which is updated every decade, (as opposed to Stage I.A which is calculated in relation to the species original status). The outputs from these stages are then combined in Stage III.D to provide an overall summary of the current influence of climate change on a species' newly colonised range (Very High, High, Moderate or Low) and an associated level of confidence (Good, Medium or Low).

Stage IV.A was based on bioclimatic projections of range change outside the current range. The percentage change in these regions was calculated as the (range in new areas)/(range in new areas +original range). Confidence was assigned as in Stage II.A. Exacerbating factors that are likely to limit range expansion, and our confidence in them, (Stage IV.C) were again based on expert knowledge and the literature. The outputs from these stages are then combined in Stage IV.D to provide an overall summary of the projected impact of climate change outside a species' historical range (Very High, High, Moderate or Low) and an associated level of confidence (Good, Medium or Low).

Stage V then combines the outputs from stages I to IV to produce an overall assessment of the risks and opportunities provided by current and projected climate change, taking into account known confounding factors.

The information required for each stage is summarised in Appendix 6.

Results – risk assessment

Basic framework
Across all species, under a 2 ˚C warming scenario, 640 species were classified as being at high risk from climate change and 188, at medium risk (a total of 27.2%). A greater number of species were regarded as likely to have a medium (486) or high (1,164) opportunity as a result of projected climate change (totalling 54.1%; Table 1.5). Under a 4 ˚C warming scenario, these estimates of risk did not differ significantly ($\chi^2_5 = 2.96$, $P = 0.71$), with 856 species projected to be at high or medium risk from climate change, and 1,644 projected to have a high or medium opportunity (Table 1.6), although there was a hint of slightly more species being classed towards the extreme end of change (high risk and high opportunity) under the 4 ˚C scenario.

Table 1.5 Cross-tabulation of the risks and opportunities associated with climate change for all species, based upon a low emission B1 projection for 2070-2099 (see Tables 1.2 to 1.4 for the definitions of each category). Values are the numbers of species in each category.

		RISK				
		VERY HIGH	**HIGH**	**MEDIUM**	**LOW**	**TOTALS**
OPPORTUNITY	**LOW**	25	1	7	6	39
	MEDIUM	614	157	481	84	1336
	HIGH	24	27	358	142	551
	VERY HIGH	56	44	662	360	1122
	TOTALS	719	229	1508	592	3048

Table 1.6 Cross-tabulation of the risks and opportunities associated with climate change for all species, based upon a medium emission A1B projection for 2070-2099 (see Tables 1.2 to 1.4 for the definitions of each category). Values are the numbers of species in each category.

		RISK				
		VERY HIGH	**HIGH**	**MEDIUM**	**LOW**	**TOTALS**
OPPORTUNITY	**LOW**	25	1	7	6	39
	MEDIUM	657	135	475	75	1342
	HIGH	31	23	343	135	532
	VERY HIGH	44	48	677	366	1135
	TOTALS	757	207	1502	582	3048

The pattern of risks and opportunities obtained when viewing only the NERC priority species (Tables 1.7 & 1.8) tended to contain slightly more ‘high risk’ and ‘medium opportunity’ species and fewer ‘high opportunity’ species than expected from the pattern across non-NERC priority species under both the B1 ($\chi^2_5 = 12.90$, *P* = 0.02) or A1B ($\chi^2_5 = 16.55$, *P* = 0.005) scenarios. Across non-NERC priority species under the B1 scenario, 27.0 % of species were regarded as being at medium or high risk from climate change, whilst 54.3 % are likely to have a medium or high opportunity. These figures change to 27.8 % and 54.1 % under the A1B projection. Of the NERC priority species, a slightly higher proportion of species were regarded as being at medium or high risk of climate change under both the B1 (30.3%) or A1B (31.6%) scenario, with a lower proportion of species thought to face opportunity (50.3% across both scenarios) than across all species. Thus, NERC priority species tended to be assessed as having a lower probability of opportunity and greater likelihood of risk under a changing climate than the average across all species.

Table 1.7 Cross-tabulation of the risks and opportunities associated with climate change for NERC priority species, based upon a low emission B1 projection for 2070-2099. Values are the numbers of species in each category.

		RISK				
		VERY HIGH	**HIGH**	**MEDIUM**	**LOW**	**TOTALS**
OPPORTUNITY	**LOW**	4	0	0	1	5
	MEDIUM	36	6	25	7	74
	HIGH	1	1	25	4	31
	VERY HIGH	3	2	35	5	45
	TOTALS	44	9	85	17	155

Table 1.8 Cross-tabulation of the risks and opportunities associated with climate change for NERC priority species, based upon a medium emission A1B projection for 2070-2099. Values are the numbers of species in each category.

		RISK				
		VERY HIGH	**HIGH**	**MEDIUM**	**LOW**	**TOTALS**
OPPORTUNITY	**LOW**	4	0	0	1	5
	MEDIUM	39	4	24	7	74
	HIGH	2	1	24	4	31
	VERY HIGH	2	4	34	5	45
	TOTALS	47	9	82	17	155

Given the similarities between the 2 and 4˚C scenarios, we focus on the 2˚C outputs to compare differences between taxonomic groups (Figure 1.4). There were significant differences between taxonomic groups in the apparent risks and opportunities resulting from climate change ($\chi^2_{64} = 488.42$, $P < 0.0001$; excluding the limited impact category due to the small sample size). The groups with the greatest proportion of species at risk from climate change were vascular plants and bryophytes (> 30 % in both cases), whilst a number of groups were largely comprised (>70 %) of species thought to face opportunity (ants, bees, centipedes, coccinnelid beetles and wasps). Individual species' assessments are summarised in the accompanying Excel file to this report (basic framework results.xlsx). Information about the habitat associations of NERC priority species was available from Natural England (Webb *et al.* 2010) . We used this information to summarise the risks and opportunities for species within each habitat, combining wetland, lakes & ponds and rivers categories into a generic (freshwater) wetland category. About half of the species were associated with more than one habitat, and therefore contributed to the assessment for multiple habitats. Across habitats, there was no significant overall variation in the risks and opportunities associated with each habitat ($\chi^2_{20} = 28.32$, $P = 0.10$), although upland habitats were the only habitat with > 50 % of species at high or medium risk of climate change, compared to only 20 % of species likely to face opportunity (Figure 1.5). The majority of urban and coastal priority species are anticipated to face opportunity from warming.

Full framework

By way of illustration, and comparison with the results of Chapter 2, which provides an assessment of the likely impacts of climate change on Annex I and migratory bird species from the results of a second bioclimate modelling project (CHAINSPAN), that related the abundance of species at sites to climate (Pearce-Higgins *et al.* 2011), we present a detailed full assessment for birds first, before summarising and analysing the results for all taxa. As above, individual species' assessments are summarised in the accompanying Excel file to this report (full framework results.xlsx).

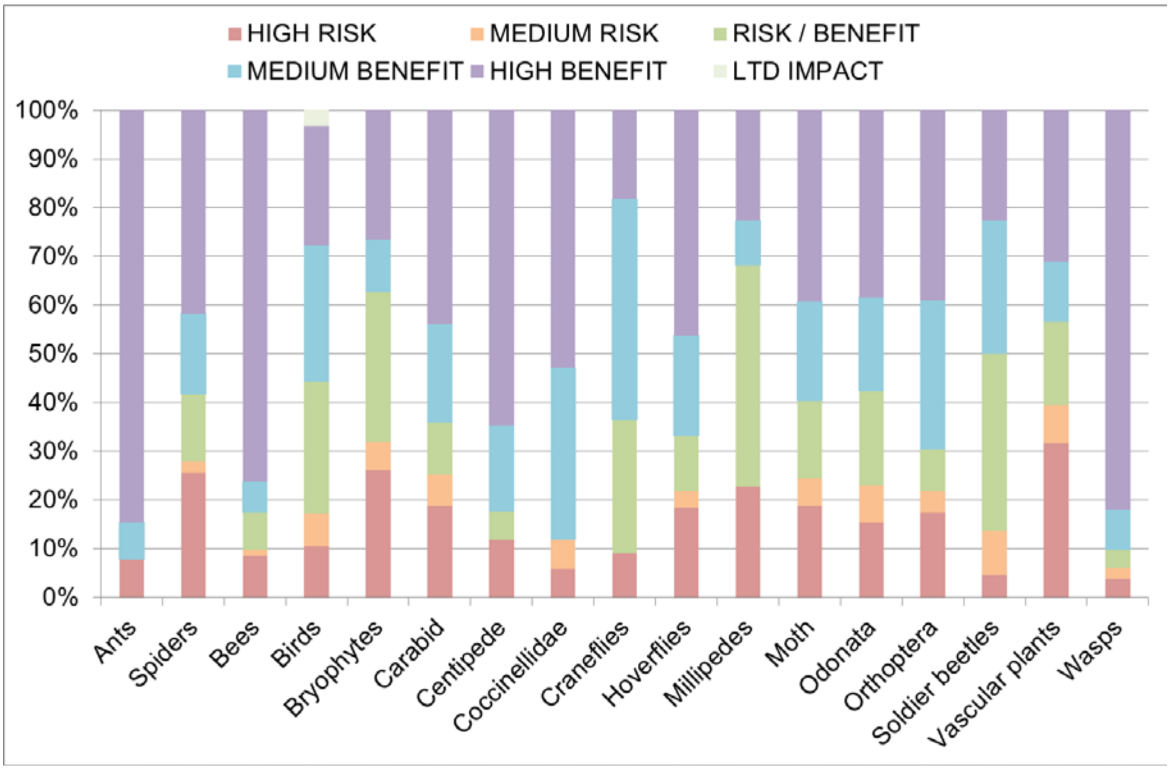

Figure 1.4 Proportion of all species categorised as likely to be at risk from climate change, or opportunity, in different taxonomic groups, as assessed by the basic framework. The sample size of species for each group is given in Table 1.1.

Birds

The results of running the 41 NERC priority bird species, plus a randomly selected additional 41 bird species through the framework devised by Thomas *et al.* (2011) for a 2 degree temperature increase scenario are shown in Table 1.9. The largest number of species (32 / 82) was assigned to the category which is at low risk from climate change-related declines, but also has a low probability of climate-change related expansions. This suggests that the distribution of these species is not mainly determined by climate related factors (often these species had projections which were in the opposite direction to observed distribution changes, which leads to the inference that climate is not the main driver of population change). There were similar numbers of species at high/very high risks of decline (with a low chance of increase) (19 species) as had a high/very high chance of opportunity from climate change (with a low chance of decline) (20 species). Therefore this particular simulation and framework suggests that there are likely to be broadly similar numbers of winners and losers under this climate change scenario. Few species have a moderate or greater risk of showing both increases and declines under this scenario. Stone Curlew and Willow tit both have very high risks of decline, but also some chance of showing climate-related increases, and Hawfinch, Goshawk and Gannet all have moderate risks of decline, but also high or very high probability of increases.

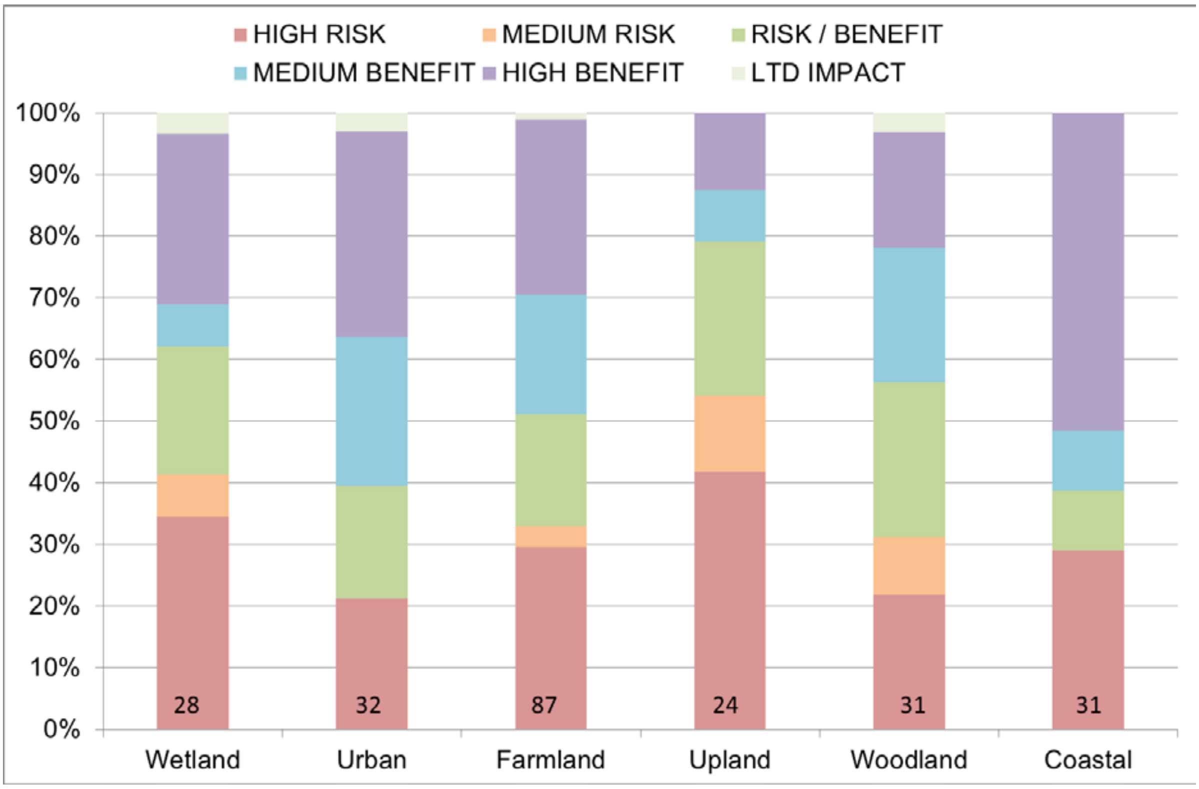

Figure 1.5 Proportion of NERC priority species categorised as likely to be at risk from climate change, or to face opportunity, according to the habitat each species is associated with. The sample size for each habitat is shown by the number on each column. About half of species contributed information to more than one habitat.

The framework was also run using bioclimatic projections made using a 4°C temperature increase scenario. For most species the projections under the two scenarios were very similar (see Fig. A4.1), and therefore the results of the framework were also almost identical. The only species that fell into a different risk/ opportunity category was the Barn owl, which moves from low risk / high opportunity category under the 2°C scenario to a low risk / very high opportunity category under the 4°C scenario.

Because of the uncertainties inherent in estimating the effects of potential future climate change, it is unsurprising that most of our categorisations of the risks and opportunities to each species were assigned a ‘low’ confidence overall. Our confidence was on average higher for the probabilities of declines than for the chance of increases in range, probably because we are more confident about factors operating within current range than those that may start to come into operation in future areas of colonisation. Of the 82 species, 11 had good confidence in their risk categorisation, 23 had medium confidence and 48 had low confidence, compared to zero with good confidence, 18 with medium confidence and 64 with low confidence for the opportunity categorisation (full framework results.xlsx).

Table 1.9 Assessment of the risks and opportunities to 82 bird species as assessed by the Thomas framework under a low emission 2 °C climate chance scenario. Forty one NERC priority species are shown in black and additional 41 randomly selected species are shown in blue. Species in bold font have at least 'moderate' confidence in the assessment of the probability of both decline and expansion.

		Risk of decline			
		Very high	**High**	**Moderate**	**Low**
opportunity for expansion	**Low**	Cuckoo, curlew, lesser redpoll, red grouse, ring ouzel, tree pipit, twite, wood warbler, garden warbler, peregrine, redstart, short-eared owl, whinchat, **barnacle goose**	Grey partridge, hen harrier, lapwing, marsh tit, dipper	Black grouse, spotted flycatcher, yellowhammer, Canada goose, merlin, treecreeper	Bullfinch, corn bunting, dunnock, house sparrow, linnet, reed bunting, skylark, song thrush, **starling,** tree sparrow, turtle dove, yellow wagtail, **blackbird,** buzzard, collared dove, coot, feral pigeon / rock dove, green woodpecker, great-crested grebe, great spotted woodpecker, house martin, kestrel, little grebe, mallard, nuthatch, oystercatcher, redshank, rook, stonechat, stock dove, whitethroat, **wren**
	Moderate	Willow tit			
	High	Stone curlew		Hawfinch, goshawk	Black-tailed godwit, cirl bunting, lesser-spotted woodpecker, Savi's warbler, woodlark, barn owl, red-backed shrike, Manx shearwater, water rail
	Very high			Gannet	Bittern, corncrake, grasshopper warbler, herring gull, nightjar, roseate tern, spotted crake, black redstart, cormorant, **Cetti's warbler,** lesser black-backed gull

The overall confidence for the predicted risk and opportunity scores depended on our confidence in Stages I to IV of the Thomas framework, and also how well the predicted and observed data agreed. Species such as starling and black-tailed godwit, where both observed and predicted changes were in the same direction, and the confidence in both were at least medium, were the species about which we can be most confident in the results. We tended to be most confident about species that were not showing climate-related declines – it was often the evidence for the link between climate and population trends that was poor, reducing our confidence in the overall assessment. However, where evidence for this link was strong, such as ring ouzel and red grouse, then we could also be confident of severe climate-related declines. This implies improved knowledge of the links between climate and population trends is necessary to understand the likely impact of climate change across species.

All taxa
Across all 402 species run through the full framework (including the birds) for a low 2 ˚C warming scenario, 141 species (35.1 %) were classified as being at high or medium risk of climate change, compared to 168 (41.8 %) which were listed as likely to have a medium or high opportunity (Table 1.10). Under a medium 4 ˚C warming scenario, 147 species (36.6 %) were classified as being at high or medium risk of climate change, compared to 166 (41.3 %) which were listed as likely to have a medium or high opportunity (Table 1.11). These results are summarised in the full framework results.xlsx. As with the basic framework results, the results of the assessments did not differ significantly between the two scenarios of warming ($\chi_5^2 = 1.54$, *P* = 0.91).

Importantly, these classifications differ significantly between the full and the basic scenarios ($\chi_5^2 = 2191.8$, *P* < 0.0001; compare Tables 1.5 and 1.10). This difference is due to 6 / 3048 species being listed as likely to have a limited impact of climate change using the basic framework compared to 75 / 402 species when the full framework was applied. As expected, the full framework presents a more realistic assessment of future change than the basic framework, because it better assesses whether observed changes can be attributed to climate change and whether there are factors that might increase the vulnerability of species to detrimental effects or constrain their ability to capitalise on potentially beneficial changes. Thus, recently observed distribution or population changes that are not related to climate change, do not contribute to the assessment, whilst potential constraints on the response of species are also considered. Once the counts in this limited impact category were deleted, there remained a significant contrast ($\chi_4^2 = 1229.6$, *P* < 0.0001) due to a greater proportion of full framework species (27.1 %) being classified as under high risk as a result of climate change than with the basic framework (21.0%), but fewer species being listed as having risks & opportunities (4.4 % with the full framework compared to 18.5 % with the basic framework) or a medium opportunity (8.2 % with the full framework compared to 15.9 % with the basic framework). Thus, the full framework produced a more negative assessment of impacts (with a greater proportion of species anticipated to suffer detrimental impacts of climate change), while also indicating that a greater number of species are likely to experience limited impact of climate change, due to more careful attribution of observed distributional changes to climate change.

An alternative comparison between the full and basic frameworks is achieved by ranking the final outcome scores from high risk (-2) to high opportunity (2) (with both ‘risks & opportunities’ and ‘limited impact’ categories scored 0) and correlating the scores achieved for individual species. When doing so in a mixed model, with taxon as a random effect, there was a high degree of correlation between basic and full framework scores ($F_{1, 398}$ = 955.56, *P* < 0.0001), with only a weak interaction between different taxonomic groups ($F_{16, 241}$ = 1.55, *P* = 0.084). The slope of this relationship indicates that a close to 1:1 relationship between scores from the two frameworks, but with the full framework on averaging producing a lower score by about 0.33 (Figure 1.6). There were no species which the basic framework assessed as being at risk from detrimental impacts that the full framework assessed as being likely to experience opportunity, although 11 regarded as likely to face opportunity using the basic framework were ranked as likely to be at risk of negative impacts under the full framework. Such results occurred when observed increases were not considered as being attributable to climate change in the full framework, or ecological constraints were regarded as unlikely to facilitate future range expansion. In general, though, the broad similarity between the full and basic framework results suggests that the latter does provide a reasonable broad assessment across the full range of species considered, but may over-estimate the likely amount of change (in cases where potentially limiting or confounding factors may be important), or provide a more positive assessment (in cases where recent population increases or range expansions cannot be attributed to climate change).

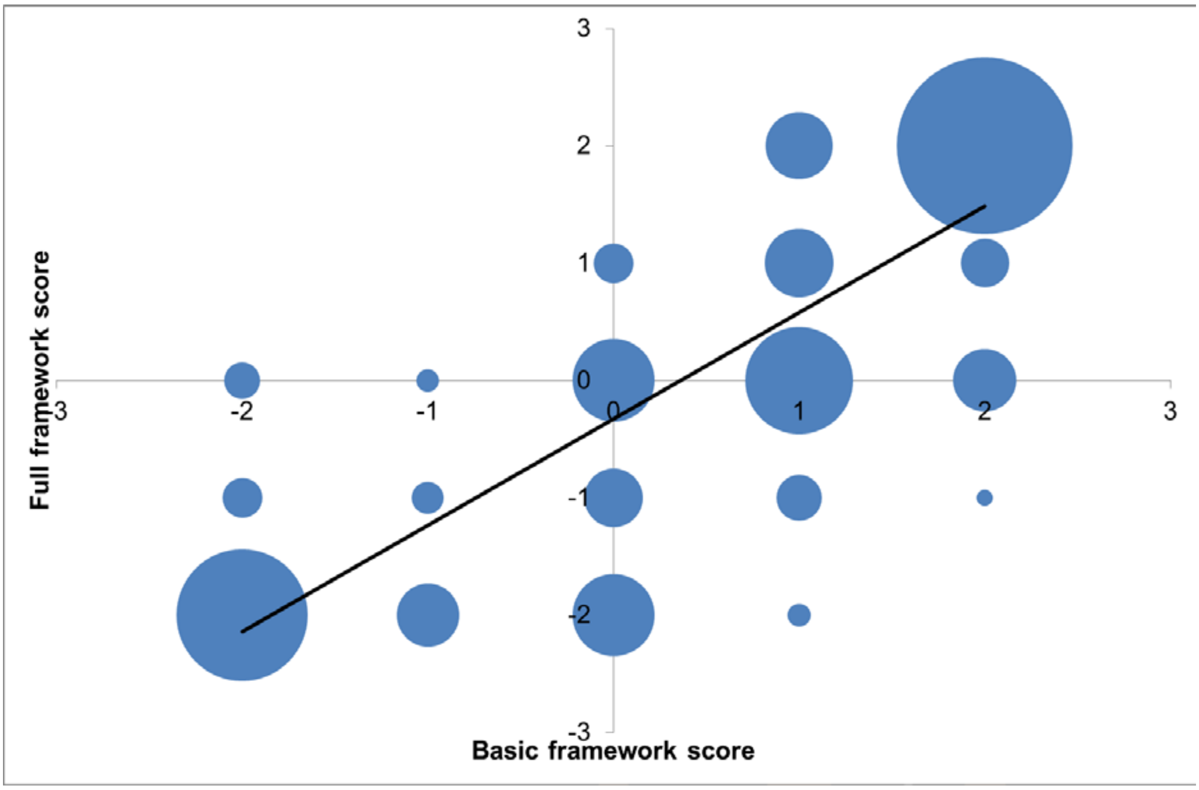

Figure 1.6 Correlation between the basic and full framework scores for the 402 species run through the full framework. The equation for the fitted line is y = -0.33+0.91x. The size of the circle indicates the number of species in each category.

When focussed just on the NERC priority species for the low 2 ˚C warming scenario, there again were few meaningful differences from the results for non NERC species ($\chi^2_5 = 10.8$, $P = 0.06$). The differences that were present were due to a greater number of species at risk (38.0 %) and fewer likely to face opportunity (38.7 %) compared to non-NERC species (33.2 % and 43.7 % respectively; Table 1.12).

There remained significant differences between taxonomic groups in the apparent risks and opportunities resulting from climate change ($\chi^2_{80} = 1170.2$, $P < 0.0001$; Figure 1.7). Bryophytes were again highlighted as the group which appear to be most vulnerable to future impacts of climate change, whilst the majority of hoverfly (7/13) species were also regarded as being at risk of climate change impacts. At least 30 % of species in a further eight taxonomic groups (spiders, birds, centipedes, millipedes, moths, dragonflies and damselflies, soldier beetles and their allies and vascular plants), were also identified as being at some risk of climate change impacts. Conversely, the large of majority of species in all three groups of Hymenoptera (ants, bees and wasps) could expand their distributions with climate change, as well as more than 50 % of carabid, coccinellid and centipede species (Figure 1.7). More than 30 % of species from the other groups could also expand their distributions, but a smaller proportion may benefit amongst the birds, bryophytes, millipedes, dragonflies and damselflies. With the exception of birds, vascular plants and moths, these assessments were based on a random selection of 13-20 species across both NERC priority groups and non NERC species, and therefore may not necessarily be representative of all species in that grouping.

Table 1.10 Cross-tabulation of the risks and opportunities associated with climate change for species from all taxonomic groups run through the full framework, based upon a low emission B1 projection for 2070-2099

		RISK				
		VERY HIGH	**HIGH**	**MEDIUM**	**LOW**	**TOTALS**
OPPORTUNITY	**LOW**	67	37	21	75	200
	MEDIUM	5	2	1	22	30
	HIGH	9	9	7	64	89
	VERY HIGH	8	4	5	66	83
	TOTALS	89	51	34	227	402

Table 1.11 Cross-tabulation of the risks and opportunities associated with climate change for species run through the full framework, based upon a medium emission A1B projection for 2070-2099

		RISK				
		VERY HIGH	HIGH	MEDIUM	LOW	TOTALS
OPPORTUNITY	LOW	80	37	18	73	208
	MEDIUM	2	2	4	20	28
	HIGH	8	7	6	65	86
	VERY HIGH	5	3	4	68	80
	TOTALS	95	49	32	226	402

Table 1.12 Cross-tabulation of the risks and opportunities associated with climate change for NERC priority species run through the full framework, based upon a low emission B1 projection for 2070-2099

		RISK				
		VERY HIGH	HIGH	MEDIUM	LOW	TOTALS
OPPORTUNITY	LOW	34	11	7	27	79
	MEDIUM	3	0	0	11	14
	HIGH	4	4	3	26	37
	VERY HIGH	5	2	1	17	25
	TOTALS	46	17	11	81	155

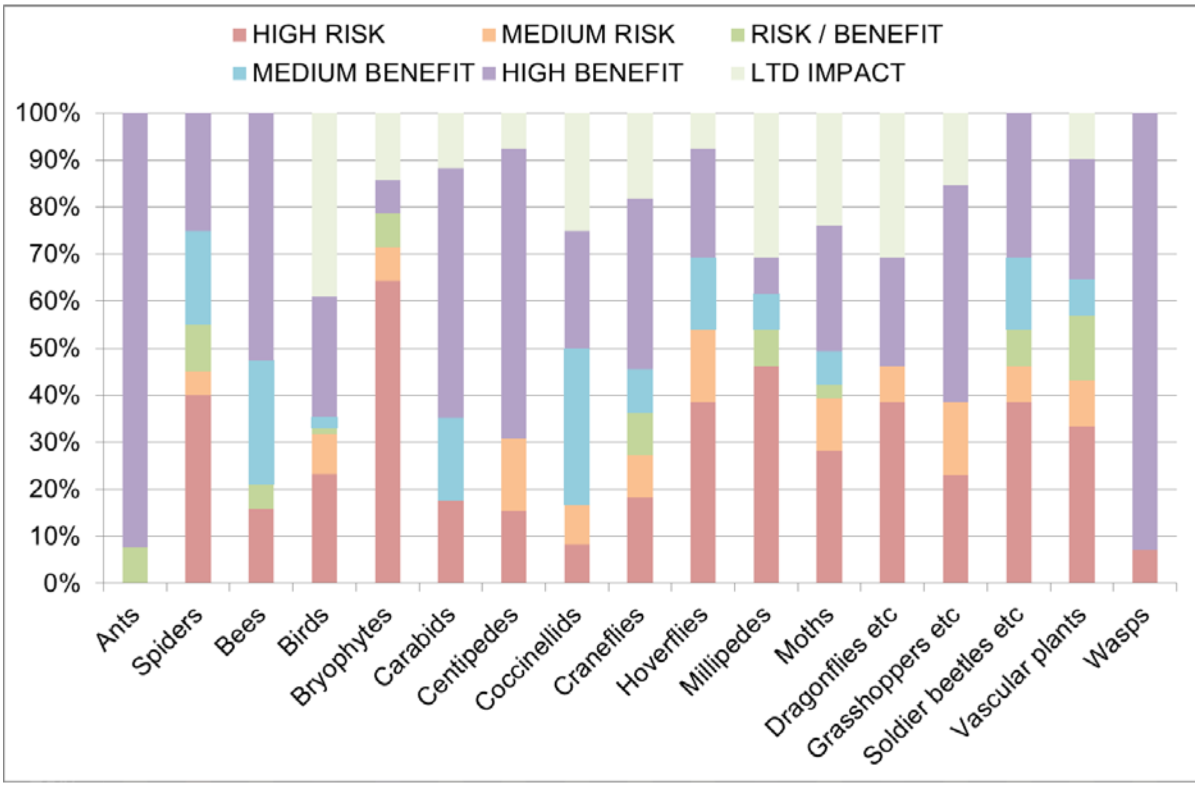

Figure 1.7 Proportion of species categorised as likely to be at risk from climate change, or to face opportunity, in different taxonomic groups, as assessed by the full framework, based upon the results of Table 1.10

Using the same approach as outlined previously for the basic framework, there was again no significant overall variation in the risks and opportunities associated with each habitat (χ^2_{25} = 33.86, *P* = 0.11). However, upland habitats appeared to be even more vulnerable to future climate change impacts and were the only habitat with > 50 % of species at high or medium risk of climate change, compared to an average of 40 % across other habitats (Figure 1.8). In fact, this frequency differs significantly from that expected from the remainder of habitats (χ^2_5 = 15.59, *P* = 0.008).

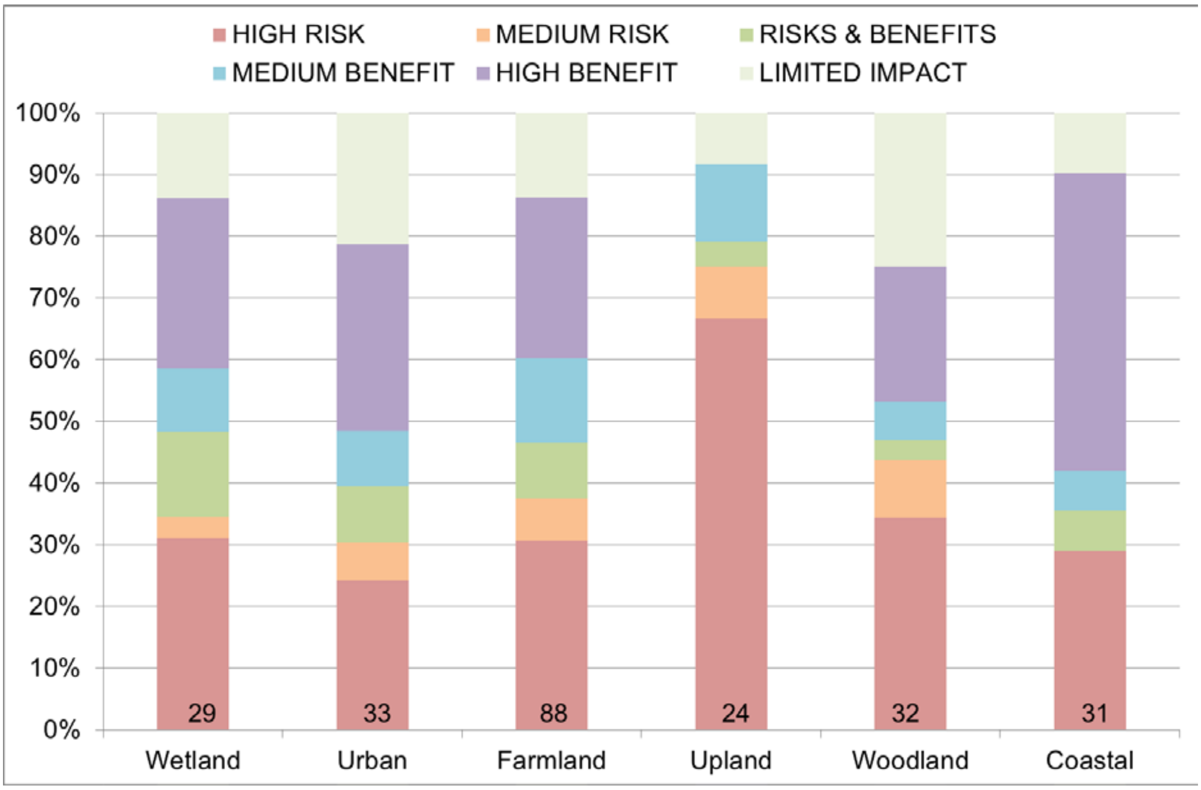

Figure 1.8 Proportion of species categorised as likely to be at risk from climate change, or to face opportunity, using the full framework, according to the habitat each species is associated with. The sample size for each habitat is shown by the number on each column. About half of species contributed information to more than one habitat.

Discussion

We used a basic framework, without any consideration of ecological factors known to influence observed changes in populations or distributions, or likely constraints on the impacts of climate change, to categorise over 3,000 species. For a significant subset of 400 of these based on 155 NERC priority species plus a random sample of the remaining (i.e. non-priority) species, these additional factors were taken into account, using the full framework, as published by Thomas *et al.* (2011). The two frameworks delivered significantly different, but broadly comparable, results, with the full framework classifying many more species as likely to experience only a limited impact of climate change. This is because the full Thomas framework incorporates information about the extent to which observed population or distributional changes are consistent with or attributed to climate change. Species that have declined due to factors other than climate change are assumed to have been affected by climate change by the basic framework. Thus, the basic framework is therefore tends to *over-attribute* observed changes to potential impacts of climate change if they are consistent with future projections, but also to *under-estimate* the potential magnitude of risks posed by climate change if observed changes as a result of non-climatic factors are opposite to future projections. However, they do provide a comprehensive assessment across taxa, and providing that they are used in the light of this caution, remain useful for species not covered by the full framework. For the same reasons, the outputs from the full framework were on the whole, more pessimistic, identifying a greater proportion of species likely to be at high risk of detrimental climate change impacts, as a result of incorporating additional information on likely constraints on the ability of particular species to respond positively.

One of the key outputs from the work appears to be that across the species assessed, there were a greater number of species projected to experience high and very high opportunities as a result of projected climate change than projected to be at high or very high risk. This was particularly the case when considering the outputs for the basic framework for all species, where over 50 % were classified with a medium or high opportunity from climate change. This finding even applies for the subset of species run through the full framework, where some 43 % of species were regarded as being likely to face opportunity from future climate change, compared to 35 % at risk of detrimental impacts, although when considering the NERC priority species run through the full framework, 39% of species were regarded as likely to face opportunity compared to 38 % at risk. The situation was similarly balanced when considering potential impacts on Annex I and migratory bird species using the full framework, where some 40 % were still classified as likely to have a medium or high opportunity compared to 38 % classified as at medium or high risk from climate change (Chapter 2). On this basis, climate change could be expected to lead to increases in the abundance of a greater number of species than those that will decline, or at least for species of greatest conservation concern, a similar number of potential beneficiaries and losers.

Whilst this may sound like a positive impact on English biodiversity, further consideration is required. There is indeed evidence that warming has been associated with an increase in species richness, particularly of birds (Davey *et al.* 2012), which matches our assessment. However, associated with this increase in richness has been a homogenisation of ecological communities, as it is widespread generalist species which have tended to increase in abundance at the expense of more specialist species that have been more likely to decline. This pattern is widespread across Europe for birds (Le Voil *et al.* 2012), and has also been recorded in Scottish mountain plants (Britton *et al.* 2009, Ross *et al.* 2012). In the UK, such homogenisation has again been related to temperature (Davey *et al.* 2012) as well as other factors (Keith *et al.,* 2009). Given our more negative future assessment for NERC priority species and Annex I and migratory bird species, which will tend to include a much greater proportion of habitat specialists than non-conservation priority species, we anticipate these future trends as likely to continue, and suggest that climate change may disproportionately negatively impact already rare and threatened species relative to common and widespread species not of conservation concern.

Our assessment may also under-estimate some negative impacts of climate change on biodiversity as a result of some methodological reasons. Firstly, with the exception of birds and vascular plants, the biodiversity data underpinning the assessment was from Great Britain only, and therefore does not fully describe the full range of climate data over which the species occurs. This could mean that potentially negative impacts associated with high levels of warming for such species may not have been identified. A test of this for birds and plants, which compared models based on British data vs. British and European data, showed that GB-only projections tended to be more pessimistic and tend towards more extreme results than those that included European data (Appendix 3). Overall, it appears that the use of GB-only projections for most groups may have inflated the projected magnitude of change for these groups slightly, and made those projections slightly more pessimistic, although outputs from GB-only projections were still strongly correlated with those that also included European data.

Secondly, there were considerable problems in being able to incorporate data on rarer or more poorly surveyed species. Thus, for 13 % of species it was not possible to generate bioclimate models and for a further 29 % of species, there was insufficient information to produce effort-corrected trends. In addition, even for the data on species that we were able to incorporate, some of the taxonomic experts associated with the non-systematic records data, consulted as part of the project who oversee specific recording schemes expressed some concern about the underpinning records data on which these assessments are made. These concerns were largely as a result of small numbers of records being provided for many species in any one year, making trend calculation difficult, the ability of observers to identify particularly difficult species, potential concerns over missing data influencing trends and the non-random nature of observer effort looking for particular species. These issues were exacerbated by the fact that the full assessment was made on a relatively small number of randomly selected and NERC priority species for most taxa, increasing the potential for these issues to influence the results. A further problem associated with the assessment is that for most of these taxa there is relatively little information about the extent to which their populations or distributions may have been impacted by climate change (as opposed to butterflies, birds and some plants). Disentangling the role of climate change from habitat loss was therefore difficult and may affect the final scoring of the assessment. Similarly, some of the potential range expansions may have been a result of conservation success, rather than necessarily climate change, even if they are consistent with that expected from climate change. A number of the species experts consulted as part of this project provided comments, which are listed in Appendix 5, and should be considered when using these results for species with particular constraints or challenges associated with their biological recording.

Thirdly, the framework is dependent upon the use of bioclimate models to make future projections of change, and to match those against recent observed population trends. There is considerable uncertainty about the likely pace of any distributional shift in response to climate change; both bird and butterfly communities appear to be lagging behind the rate of warming observed across Europe (Devictor *et al.* 2012); non-mobile groups such as many of the plants may well lag even more. Further, the ability of a species to disperse will be an important constraint on the extent to which a species can occupy any new areas of potential range in the future (Barbet-Massin *et al.* 2012), as will the availability of areas of potentially suitable habitat for colonisation (Thomas *et al.* 2012). Although there remains considerable uncertainty about the pace of these responses to climate change, these uncertainties are captured by the Thomas *et al.* (2011) framework, enabling species with constrained capacity to disperse into areas that become newly climatically suitable, to be scored as having a lower likelihood of opportunity as a result of climate change than other species which are not dispersal-limited. In addition, we assume that the bioclimate models fully describe the impacts of climate change, as also discussed in Chapter 4 methods. Whilst they probably do capture the main elements of variation for terrestrial taxa, for coastal and marine taxa, where spatial patterns of changes in sea temperature may differ from those on land, projections are likely to be less certain. We also have not considered potentially detrimental impacts of sea-level rise upon vulnerable coastal habitats and species (e.g. Gilbert *et al.* 2010).

Despite the caveats, there are also good reasons to expect that Great Britain may be located in an area where the impacts of climate change may on balance, be more positive than negative, when considered across all taxa. This is because more species are at their northern range margins in the UK than at their southern range margins (e.g. butterflies: Asher *et al.* 2001; plants: Preston *et al.* 2002). Other assessments of projected future impacts of climate change on European species' distributions have also highlighted that the UK is in a region where many species might be expected to expand their range extent, whilst range contractions and declines are more likely to occur elsewhere (Araújo *et al.* 2011). Indeed, the previous application of the Thomas framework, applied to British butterflies, also found this to be the case, although butterflies do tend to be thermophilous by nature. Of the 55 species considered, three northern / upland species were regarded as at high risk (small mountain ringlet, Scotch argus, and northern brown argus) and three at medium risk (pearl-bordered fritillary, small pearl-bordered fritillary and large heath) from climate change, but 27 were regarded as likely to suffer limited impact, 10 medium opportunity and 12 high opportunity (Thomas *et al.* 2011). We have already discussed the increase in the richness of the British bird community associated with warming, which was also associated with a progressive homogenisation, as generalists spread and specialists declined (Davey *et al.* 2012). Our results therefore suggest that across England, there are a large number of species whose distribution is currently limited by climate (probably by low temperatures in many instances), and that future climate change is likely to result in a significant expansion of their geographical distribution. Thus, recent observations of the range expansion of southerly distributed species would be expected to continue (Hickling *et al.* 2006, Thomas *et al.* 2012, Hiley *et al.* 2013).

There remained a significant number of species projected to be at risk of climate change, particularly in upland habitats, where increasing temperatures might be expected to result in northern and upwards range contraction, or wetland habitats, where species may be vulnerable to drought. Certainly other studies have suggested that northern or upland birds (Green *et al.* 2008, Pearce-Higgins 2010, Renwick *et al.* 2012) and butterflies (Thomas *et al.* 2011) may be particularly vulnerable to climate change compared to southern species. For example, the majority of Annex I and migratory bird species projected to be at risk of climate change were northerly distributed breeding seabirds or upland birds, whilst those projected to experience opportunity with greatest confidence tend to have a southern distribution (Pearce-Higgins *et al.* 2011). The actual mechanism by which cold adapted species are excluded at lower latitudes or altitudes will vary. There is increasing evidence that population changes in response to climate change may be driven by changes in interactions between species, such as through predation, prey or potential competitors (Cahill *et al.* 2012, Ockendon *et al.* 2014). There is already good evidence of these processes impacting upon upland birds (Pearce-Higgins *et al*. 2010, Pearce-Higgins 2010). Research to better understand drivers of changes in cold adapted species should therefore be prioritised to inform subsequent management responses (e.g. Pearce-Higgins 2011).

Such geographical differences may also account for the apparent high sensitivity to future climate change of many bryophytes (Figures 1.4, 1.7), many of which are likely to have a northern or north-western distribution and tend to thrive in cool and damp conditions. Our analysis suggests that of all the taxonomic groups considered, they are likely to be most vulnerable to future climate change impacts, although to be surer of this the full framework assessment could be usefully extended to a greater proportion of the species covered by the basic framework. In a recent review (Ellis 2013), the potential impacts of climate change on oceanic bryophytes was regarded as uncertain, whilst northern and upland species are anticipated to be detrimentally affected. Although there is some evidence for recent warming being associated with distribution shifts for some species, there are difficulties in disentangling these changes from improvements in atmospheric pollution. Conversely, Hymenoptera species, the majority of which have a southern distribution, appeared particularly likely to experience opportunity from climate change, matching the results of a previous review which showed that populations of many Hymenoptera increase with warmer temperatures (Pearce-Higgins 2010). Thus, although many taxonomic groups contain some species likely to be at risk from climate change and others likely to face opportunity, the relative preponderance of the two will vary with the geographical and habitat bias of that group, as well as the ecological characteristics of the species, such as voltinism, diapause strategy, migratory strategy and growth rate (Bale *et al.* 2002).

To conclude, this study provides the first comprehensive assessment of the likely impacts of climate change on a wide range of taxa in a particular country. The results support previously suspected relationships regarding the sensitivity of particular taxa and habitats to climate change, but present these for individual species in a standardised and repeatable way. Further, for the species to which the full framework was applied, these results are the product of a detailed assessment incorporating additional ecological information about potential constraints on the ability of species to respond to climate change. These species-specific results should continue to be interpreted in the light of ecological knowledge of the species involved (particularly for those only assessed using the basic framework), but we hope that these findings may be used to help adapt nature conservation in England to a changing climate.

2 Additional assessment of risks and opportunities for Annex 1 and migratory bird species

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Introduction

We carried out an additional set of assessments of the risks and opportunities of climate change using 74 Annex 1 and migratory bird species as listed on the EU Birds Directive, plus an additional 12 species which were considered likely to colonise the UK in the coming decades. The abundance of these species had been modelled as a function of climate as part of the CHAINSPAN project (Pearce-Higgins *et al.* 2011), which investigated the resilience of the SPA network to climate change. Importantly, this includes an assessment of impacts on internationally important non-breeding species not covered by the assessment in Chapter 1. These assessments are also based upon projections of abundance rather than occurrence, and may therefore provide more information of value to conservationists. It is also instructive to assess the commonality of results from the CHAINSPAN project and from this project, as presented in Chapter 1, for the species covered by both. CHAINSPSAN projected changes in abundance of species and assemblages at SPAs across Europe under several climate change scenarios using UKCP09 and European ensemble data.

Methods

The species modelled in the CHAINSPAN project were those for which SPAs have been designated and sufficient data exist, and included a large number of wintering waterbirds, breeding seabirds and scarce breeding species, as well as a few breeding waterbirds (see attached spreadsheet Annex 1 & migratory species results.xlsx). In addition, species which are expected to colonise Britain under climate change were identified on the basis of projections from bioclimatic models of birds in Europe (Huntley *et al*. 2007) as well as expert opinion of birds' current distributions and patterns of movement. As well as British data, results from surveys in other northern European countries were included in model construction, which provided information about species' responses to a wider range of climatic conditions (Pearce-Higgins *et al.* 2011). In order to assess risks and opportunities for these species we used the projections of abundance change under a medium (A1B scenario of global climate change (equivalent to 4ºC warming)) scenario by 2050 from the CHAINSPAN models.

Therefore, for this section of the project we used the results of models of species' projected change in abundance, which may provide more detailed information than those based on distribution extent alone (Howard *et al.* 2014). However, because these projections were only calculated for sites where species were already present, they were not split into 'current' and 'future' range as the Thomas *et al*. (2011) framework proposes. Instead there was a single value, representing the projected national change in abundance for each species, and therefore this component of the project required modification of the Thomas framework. This was achieved by using the species' projected abundance change value to represent projected change in both Stage II (recent range) and Stage IV (future range) of the Thomas framework. This resulted in at least one of these stages having an impact of 0 (or both if the decadal population change was <1% and >-1%), as one scale focussed only on range expansion, and the other, on range contraction.

Observed population changes were also based on abundance changes in order to allow comparison with the CHAINSPAN models. Wintering waterbird data were based on survey data from the Wetland Bird Survey (WeBS), breeding seabird trends on information from Seabird 2000 (Mitchell *et al.* 2000), and other breeding species on data from the Breeding Bird Survey from 1994-2011 (Risely *et al.* 2012), or species-specific surveys. Confidence in these population trends was classified as good for all species except terns, which were not well-surveyed by Seabird 2000 due to movements between colonies within a survey, and fluctuating proportions of non-breeders. Similarly to the projections, only a single value of observed population change was available for each species across Britain, and this value was used in both Stage I.A and III.A.

Only Stage IV could be completed for new colonising species as there is currently no observed population trend for these species in the UK. All species which had not been recorded in the UK were scored as predicting a >7.5% increase in Stage 4A (as the recent population = 0).

Other sections of the framework were completed as described in the methods section of Chapter 1 for all species. Species outputs from the framework are given in the accompanying Excel file (Annex 1 and migratory species results.xlsx).

Outputs for the CHAINSPAN species were then run through the Oliver framework in order to assess likely adaptation options (Oliver *et al.* 2012); see Chapter 4. Because the projections for CHAINSPAN were not split between locations where the species is projected to decline and those where it is projected to colonise, but instead provide an assessment of likely population change for the whole country, we used following decision trees:

- for species with a high or very high risk of decline, and low likelihood of opportunity, we focussed on the decision tree for adversely sensitive areas (Table 2 in Oliver *et al.* 2012);
- for the other species present in the UK we focussed on the climate overlap decision tree (Table 3 in Oliver *et al.* 2012).
- for potential colonists, we focussed on the new climate space decision tree (Table 4 in Oliver *et al.* 2012).

We defined populations as self-sustaining where the current population trajectory which result in a smaller than 25 % decline over 25 years (the threshold criterion for amber conservation listing on the IUCN Red List). Other information required for the Oliver framework was derived from the review of potential exacerbating factors collated for the

Thomas framework, which were based on a combination of expert knowledge and a review of the literature.

Table 2.1 Likely opportunity of climate change for Annex I and migratory bird species based on results from the CHAINSPAN project. (w) indicates wintering populations and (p) passage populations. Species in italics were associated with very poor models, and those in bold have moderate or good confidence for both assessments of risk and opportunity.

		Risk of decline			
		Very high	**High**	**Moderate**	**Low**
opportunity for expansion	**Low**	*Sandwich tern,* Arctic tern, LT duck (w), *pochard (w), greylag goose (w),* curlew	Fulmar, kittiwake, mallard (w), eider (w), dotterel	Razorbill, puffin, guillemot, *common gull, Bewick swan (w),* whooper swan (w), bar-tailed godwit (w), *gadwall (w),* tufted duck (w), wigeon (w), goosander (w), GC grebe (w), *little grebe (w),* coot (w), cormorant (w), *velvet scoter (w),* pink-footed goose (w), oystercatcher (w), lapwing (w), purple sandpiper (w)	Redshank (w), pintail (w), **bittern,** knot (w), **GBB gull,** shag, *common tern, gannet,* redshank
	Moderate			Goldeneye (w)	Herring gull, black-headed gull, turnstone (w), RB merganser (w), little tern, dunlin (w), ringed plover (w), scaup (w)
	High				*LBB gull, cormorant,* curlew (w), golden plover (w), snipe (w), common scoter (w), red-throated diver (w), red-throated diver, black-throated diver, stone curlew, woodlark, nightjar
	Very high				**Avocet (w),** black-tailed godwit (w), **sanderling (w),** grey plover (w), greenshank (w), teal (w), shelduck (w), shoveler (w), Slavonian grebe (w), brent goose (w), **Dartford warbler,** chough, **little egret (p)**

Results

Full Thomas et al. framework

Because the assessment for these species only considered projected and observed population changes within the current range, outputs were largely limited to species either being classified as at risk or opportunity from climate change (Table 2.1). Of the 74 species covered, excluding colonists, 11 were regarded as at high risk from climate change and 20 at medium risk. Conversely, 25 of these species were projected as likely to experience a high opportunity from climate change, and 8 a medium opportunity. Nine species were regarded as likely to face a limited impact from climate change, whilst wintering goldeneye populations was categorised under risks and opportunities. Most of the species with the greatest risk of decline were breeding seabirds (Sandwich tern, Arctic tern, fulmar, kittiwake, razorbill, puffin, guillemot, common gull) or breeding upland birds (curlew and dotterel). The other large group of species investigated, wintering waterbirds, contained a mixture of species projected to be at risk from climate change (21) and those predicted to face opportunity (20).

Of the 12 colonising species tested, three were regarded as likely to have a high opportunity from climate change, whilst six were modelled as unlikely to colonise (Table 2.2). The latter group of species tended not to be significantly related to climatic variables, although it is worth noting that the abundance data for many of these species was fairly limited, being dependent largely upon French BBS data as opposed to bespoke survey data. This means that they were recorded from only a relatively small number of survey locations.

Of 74 assessments of the risk of decline, 35 were associated with moderate or good confidence. All but two of these were of low risk, with the exception of Dotterel and Curlew, both of which were categorised as being at very high risk of future climate change impacts with moderate confidence. Only 21 of the assessments of opportunity (which also included consideration of potential colonists) were associated with moderate or good confidence. Again, the majority of these were for low opportunity, with the exceptions of very high opportunities for the expansion of wintering Avocet, wintering Sanderling, passage Little Egret and breeding Dartford Warbler populations and moderate likelihood of expansion for Black Woodpecker. It seems realistic to classify most of our assessments of risk and opportunity as having moderate or poor confidence given that they are based on models which often contain a high degree of uncertainty, and are in turn based on climate projections which are based on probabilities of different scenarios. Even for many of the bird species covered, information about the possible exacerbating factors and constraints on expansion are relatively poorly understood. The confidence in species' assessments was higher when the models and observed data predicted similar trends, and where our confidence in the projection was higher, because it was based on good quality and quantity of data, and where the species' distribution is mainly limited to climate. Assessments for breeding bittern, great black-backed gull, curlew, Dartford warbler and redshank, and non-breeding little egret, sanderling and avocet populations were those associated with the greatest confidence (medium or good for both risk of decline and benefit of expansion).

Table 2.2 The likely opportunity the 12 colonising species will gain from climate change, as assessed from the CHAINSPAN project. (w) denotes wintering populations

Opportunity for expansion	**Low**	Green sandpiper (w) Ferruginous duck (w) Tawny pipit Night heron Kentish plover Whimbrel (w)
	Moderate	Black woodpecker Ortolan bunting Purple heron
	High	Red crested pochard (w) Great white egret (w) Little bustard

Comparison with the full framework results

Ten species were assessed using both the CHAINSPAN models, and the bioclimate models of Chapter 1 (Table 1.9 – see Table 2.3). Of these, three were allocated to the same risk / opportunity category by both analyses (Curlew, redshank and woodlark). Five remained in the low risk of decline category from both models, but their predicted opportunity due to climate change was higher when Chapter 1 bioclimatic models were used rather than CHAINSPAN ones. This was likely to have been due to the significant increases observed outside the historic range for all species from Atlas data (Stage III of the Thomas framework).

Table 2.3 Comparison of results in Table 2.1 with those of Table 1.9. Black=Assignment from Table 2.1, red= Bioclimatic model assignment from Table 1.9. Species in bold remain in same category under both models. Others are linked by lines.

		Risk of decline			
		Very high	**High**	**Moderate**	**Low**
opportunity for expansion	**Low**	**Curlew**			**Redshank** (Gannet) Bittern
	Moderate				Herring gull
	High	Stone curlew			**Woodlark** Stone curlew (LBB gull) (Cormorant) Nightjar
	Very high			Gannet	Nightjar Cormorant LBB gull Herring gull Bittern

The risk of decline changed for only two species between the two approaches. For Stone curlew the opportunity category stayed the same, but the risk of decline changed from 'low' to 'very high'. This was because of observed and projected declines in stone curlew distribution from bioclimatic models and Atlas data (used in our bioclimatic models), whereas CHAINSPAN predictions and Scarabbs survey data both showed increases in stone curlew abundance (used in CHAINSPAN section), hence the previously low assessment of risk. Gannet was projected to decline within current ranges and increase outside current range, and was also observed to be increasing outside the current range in the present study, whereas the CHAINSPAN results suggested that there was no link between climate and population trends. Overall, six of the ten species remained in the same broad category across both approaches.

The CHAINSPAN assessment may underestimate opportunity relative to the bioclimate models of Chapter 1, as they do not specifically incorporate range expansion (population increases within the current range were used to identify benefits). However, the underpinning models for the CHAINSPAN assessments have been shown to have good predictive power when compared against recent population trends (Johnston *et al.* 2013), and therefore may be expected to also generate reasonable projections of the future, at least in the short- to medium-term. There is also increasing evidence that such models of abundance may better describe species' responses to climate than models of occurrence (Howard *et al.* 2014). The CHAINSPAN models also provide the only information for passage and wintering species, for which bioclimate models were not produced due to the lack of distribution data. When making assessments for Annex I and migratory species, we therefore recommend that the results of both assessments be viewed together, particularly given the additional information contained within the abundance data the CHAINSPAN models are based on. However, given that the CHAINSPAN models are of abundance rather than occurrence, they may potentially under-estimate benefit compared to the Chapter 1 bioclimate models because they do not allow for colonisation of currently unoccupied habitat. For some purposes, particularly if interested in the potential for range expansion, the Chapter 1 models may therefore be more appropriate to use.

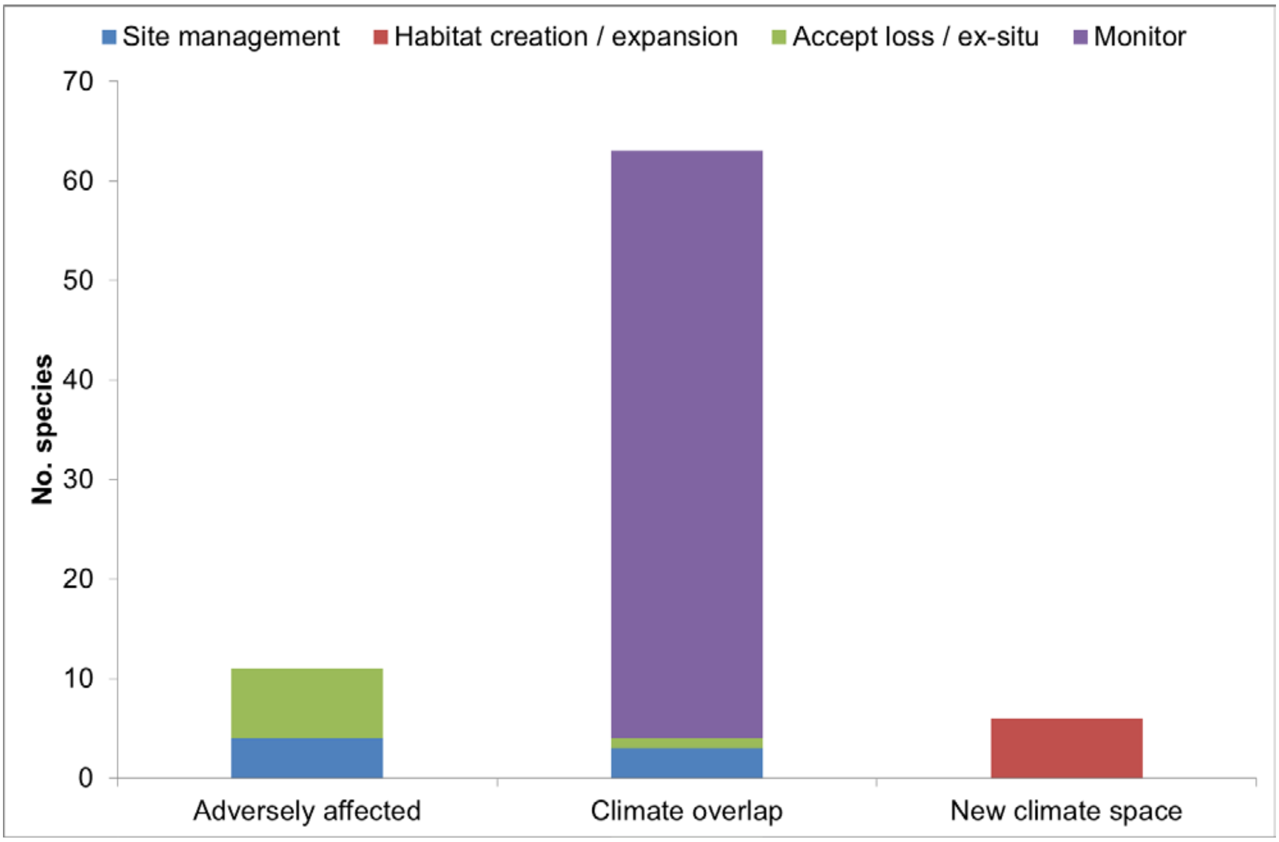
Climate change adaptation framework
Eleven species were identified as likely to be adversely affected by climate change (Figure 2.1). Of these, seven are currently declining at a rate that gives a 25 % decline or more over 25 years, and therefore were not regarded as self-sustaining in the UK. These were sandwich tern, Arctic tern, kittiwake, long-tailed duck (w), pochard (w), dotterel and curlew, and therefore, according to the Oliver *et al.* (2012) framework, may be regarded as requiring *ex-situ* conservation or the need to accept losses, although changes in wintering distribution in particular may reflect large-scale redistributions (Nilsson 2005, 2008, Lehikoinen *et al.* 2013). However, it should be noted that our analysis here dealt with the UK as a single unit and the whole of the UK might not actually be equally vulnerable. More detailed analyses at a finer spatial scale might identify areas of climate overlap for these species where conservation actions would be more effective and where the Oliver framework would recommend actions be focussed. In the genuine absence of areas of climate overlap in the zone of study, practitioners may still decide to act to attempt to ameliorate species declines. It should be noted that for at least four of the species considered, it is possible to identify current pressures and exacerbating factors that could be addressed in order to increase the likelihood of the population being self-sustaining. For example, reducing the pressure from existing sandeel fisheries on fish populations may benefit both Arctic terns and kittiwakes (Uttley *et al.* 2009, Frederiksen *et al.* 2004), whilst appropriate habitat management (van der Wal *et al.* 2003, Grant & Pearce-Higgins 2012) may assist the conservation of both dotterel and curlew, with evidence that predator control and managing woodland expansion may be particularly important for the latter (Grant *et al.* 1999, Fletcher *et al.* 2010, Douglas *et al.* 2014). Of the remaining four species projected to be adversely affected by climate change, populations were regarded as more likely to be self-sustaining, and therefore *in-situ* site management was recommended for fulmar, mallard (w), eider (w) and Icelandic greylag goose (w).

Of the 63 species regarded as potentially likely to experience opportunity from climate change, all but four were regarded as having self-sustaining populations (population trends that are equivalent to being stable, increasing or declining by less than 25 % over 25 years). For the majority of species, the Oliver framework therefore simply recommends monitoring and research. For the remaining four species, buffering edge effects and *in-situ* site management were recommended for breeding little tern and redshank sites (as the extent to which negative edge effects may be important is unclear for these species). For little terns, reducing levels of human disturbance and predation pressure may be important (Ratcliffe *et al.* 2000), whilst appropriate management of both saltmarsh and grazed farmland may improve habitat quality for redshank (Norris *et al.* 1998). For the other two species, shag and dunlin (w), there may be limited potential to improve existing habitat quality, although for the former, reducing pressure on the sandeel fishery may also be beneficial.

Six potential colonists were identified, all of which are likely to require habitat creation to facilitate colonisation. Thus, both purple herons and great white egrets are likely to require expanded and improved quality wetland and reedbed habitats for a self-sustaining population to be maintained (Grulll & Ranner 1998, Barbaud *et al.* 2002, van der Hut *et al.* 2008, Voslamber *et al.* 2010). Any wintering red-crested pochard are likely to require lakes with good water quality to maintain a healthy stonewort crop (Ruiters *et al.* 1994). Black woodpeckers are associated with large areas of old growth pine and beech woodland (Tjernberg *et al.* 1993, Fernandez & Azkona, 1996, Garmendia *et al.* 2006), whilst both ortolan bunting and little bustard are strongly associated with extensively managed farmland (Salamolard & Moreau, 1999, Wolff *et al.* 2001, 2002 Golawski *et al.* 2002, Berg 2008). Of course, the extent to which these species are likely colonise England will depend upon their dispersal ability, which is likely to be particularly limiting for black woodpeckers, and on favourable population trends in Europe, to maximise the potential for dispersing individuals.

The framework appears to have identified a large number of species for which monitoring is required, but no further immediate action. These are species likely to be at a low risk of decline as a result of climate change, but whose populations also appear largely sustainable. More than half of species projected to be at high risk of loss were identified as either requiring *ex situ* conservation, or that the loss of the species should be potentially accepted. However, finer spatial scale analyses (e.g. sub-UK level) may demonstrate some degree of opportunities exist for both categories of these high-risk species, and should be used to explore whether areas of climate overlap do exist where conservation actions might have the best chances of success. Even in light of widespread declines some mitigating adaptation actions could potentially improve outcomes for these species. As well as management actions for declining species, habitat creation or modification are also suggested to be required to allow self-sustaining populations of new bird species to colonise Britain.

Figure 2.1 Summary of adaptation outcomes from the Oliver framework for Annex I and migratory species from CHAINSPAN, plotted by whether they are likely to be adversely affected by climate change, colonise England (new climate space) or show only a low to moderate risk of loss (climate overlap)



3 Adapting bird conservation management to climate change

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Introduction

Below, we summarise some of the key implications of the results of the assessment (Chapters 1 and 2) for management of habitats for birds. We do this by considering, for each main habitat (and for seabirds), measures which are likely:
1) To increase the resistance of populations of SPA and NERC priority bird species assessed as being at medium or high risk of climate change-related decline in the UK; and
2) To be needed to provide suitable habitat for the expansion of SPA and NERC priority bird species assessed as being of medium or high likelihood of climate change-related opportunity.

Key actions predicted to benefit SPA and NERC priority bird species in each habitat are summarised in Table 3.1.

Table 3.1 A summary of suggested key adaptation actions to assist populations of SPA and NERC priority bird species in different habitats, based on the analysis in this chapter

Red = high risk of decline; pink = medium risk of decline; purple = high opportunity; blue = medium opportunity; dark green = risk & opportunities; light green = limited impact; No colour = not assessed.

Habitat	Action	Main species predicted to benefit
Freshwater & brackish wetlands	Creation of freshwater wetlands to benefit species whose range expansion is otherwise likely to be limited by low habitat availability (& to offset predicted loss of coastal freshwater reedbeds)	Night-heron, bittern, purple heron, black-tailed godwit, Savi's warbler, little bittern, great white egret, spoonbill, common crane, plus many other wetland species
	Creation of brackish wetlands (containing nesting islands) to benefit species whose range expansion is otherwise likely to be limited by low habitat availability	Sandwich tern, Kentish plover, common tern, little tern, avocet, spoonbill, plus many other wetland species
	Improvement of water supply & hydrological control at wetlands in east & south-east England	Lapwing, night-heron, bittern, purple heron, black-tailed godwit, Savi's warbler, little bittern, great white egret, spoonbill, common crane, plus many other wetland species
	Measures to reduce eutrophication	Night-heron, bittern, purple heron, little bittern & great white egret, pochard, coot, gadwall, red-crested pochard & other wildfowl that feed on submerged macrophytes
	Killing of foxes	Lapwing, black-tailed godwit
Intertidal habitat	Creation of intertidal habitat through managed realignment or regulated tidal exchange to offset losses from coastal squeeze	All species which use muddy intertidal habitat
	Reduction in unsustainable shellfisheries	Oystercatcher, knot, & shelduck and possibly other species
Lowland heathland	Creation of lowland heathland to benefit species whose range expansion is otherwise likely to be limited by low habitat availability	Woodlark, nightjar & Dartford warbler
	Prevention of high levels of human disturbance	Tawny pipit, woodlark, nightjar, Dartford warbler & red-backed shrike
Lowland farmland	Implementation of relevant agri-environment scheme prescriptions	Grey partridge, lapwing, yellowhammer, turtle dove, yellow wagtail, skylark, starling, tree sparrow, linnet, reed bunting, corn bunting, stone-curlew & cirl bunting
	Interventions to increase breeding productivity of stone-curlews on farmland	Stone-curlew

Habitat	Action	Main species predicted to benefit
Upland heath, blanket bog & in-bye	Blocking artificial drainage on blanket bog	Golden plover, & probably also dunlin, snipe & curlew
	Legal control of generalist predators	Red grouse, golden plover, lapwing, curlew & black grouse
	Removing (i.e. not re-planting) conifer plantations in inappropriate areas	Golden plover & snipe
	Providing suitable feeding conditions on in-bye land	Hen harrier, golden plover & dunlin
	Prevention of illegal persecution	Hen harrier & peregrine
	Rotational heather burning	Red grouse
	Temporary reduction in grazing pressure	Black grouse
	Controlling human disturbance	May be locally important for a range of upland species
Lowland broadleaved woodland	Diversification of woodland structure (including through reducing deer browsing pressure), providing a mix of suitable native tree species, and increasing the size of individual woodlands (and for some species clusters of woodlands in close proximity)	Probably many species, but limited evidence
Seabirds	Reduction in unsustainable fishing of sandeels	Arctic tern, guillemot, puffin & kittiwake
	Prevention of colonisation of important seabird nesting islands by rats, and eradication of rats on potentially suitable seabird nesting islands	Puffin, Sandwich tern, Arctic tern, storm petrel, common tern, Manx shearwater & roseate tern
	Creation of suitable coastal islands for nesting terns, especially as part of intertidal habitat re-creation schemes	Sandwich tern, Little tern & common tern

Freshwater and brackish wetlands

The majority of SPA and NERC species which breed in freshwater and brackish wetlands in the UK, which were assessed using the framework, were considered likely to face opportunities from the impacts of climate change, or to be largely unaffected by the climate change scenario considered (Table 3.2). The risks and opportunities of several additional rare Annex I breeding species could not be reliably assessed, because their breeding distribution has significantly changed in the UK and near-Continent since the EBBC Atlas (on which species European distribution has been modelled) was produced. Four species have started regularly breeding in Britain in this period (little bittern, great white egret, little egret, and spoonbill), whilst common crane has increased its breeding range in the UK despite simulations of present and potential distributions showing the UK being climatically unsuitable for it. The results of the analysis of CHAINSPAN species also suggest that purple heron and possibly night-heron could begin regularly breeding in the UK, while the results of Huntley *et al.* (2007) suggest that the UK could become suitable for regular breeding by several additional wetland species. The high proportion of breeding freshwater and brackish wetland species assessed as likely to face opportunities from the impacts of climate change in the UK, reflect the general increase in species-richness of lowland wetland birds breeding in warmer climates to the south of the UK.

The results of the assessments for bittern, marsh harrier, avocet and black-tailed godwit are likely to have over-assessed the potential opportunities of climate change for these species. This is because the observed increases in UK populations of these species are undoubtedly due largely to conservation interventions, or combinations of conservation interventions and recovery from past human-induced population declines, rather than solely due to changes in climatic conditions.

For the wintering/passage populations, there were slightly more species assessed as being at high or medium risk of decline, compared to being at medium or high likelihood of opportunity from the impacts of climate change (Table 3.3). The majority of species at risk were diving species (great-crested grebe, little grebe, cormorant, pochard, tufted duck, goosander and coot), while the majority of species assessed as likely to face opportunities from the impact of climate change were species which feed mainly in shallow water (shoveler & teal) or on soil macro-invertebrates on wet grassland (lapwing, golden plover, curlew and snipe). These differences might reflect changes in the current and predicted extent of freezing of water bodies and upper soil in the UK in winter. The future climate scenario considered might allow diving species (which require relatively deep water which is less likely to freeze over than shallow water) to winter increasingly further northeast of the UK. It might also allow populations of species that feed more in shallow water or on soil macro-invertebrates on wet grassland (whose wintering populations in the UK are probably currently probably towards the northern edge of climatic tolerance due to frequent freezing of shallow water and the upper soil in much of the UK under the current climate) to increase due to increased frequency and duration of shallow water and upper soil. Rapid, north-easterly shifts in wintering distribution of the diving species tufted duck, goosander and goldeneye have already been observed in northern Europe during the last three decades (Lehikoinen *et al.* 2013).

Table 3.2 Risks and opportunities for SPA and NERC priority bird species breeding at freshwater & brackish wetlands. For SPA species, we have listed all Annex I species which currently breed in England (even if they do not have SPAs currently classified for them).

Full framework = results from the assessment using the full Thomas et al (2011) framework, based on the results of bioclimatic modelling carried out as part of the current study.

Full framework (CHAINSPAN) = results from the assessment using the full Thomas *et al* (2011) framework, based on the results of bioclimatic modelling carried out as part of the CHAINSPAN project.

Species	**Status**	**Results of risks & opportunities assessment**	
		Full framework	**Full framework (CHAINSPAN)**
Lapwing	NERC priority	High risk	-
Ruff	Annex I	High risk	-
Cuckoo	NERC priority	High risk	-
Kingfisher	Annex I	High risk	-
Night-heron	Annex I potential colonist	-	Low opportunity
Kentish plover	Annex I potential re-colonist		Low opportunity
Yellow wagtail	NERC priority	Limited impact	-
Reed bunting	NERC priority	Limited impact	-
Purple heron	Annex I potential colonist	-	Medium opportunity
Bittern	Annex I	High opportunity	Limited impact
Marsh harrier	Annex I	High opportunity	-
Spotted crake	Annex I	High opportunity	-
Avocet	Annex I	High opportunity	-
Black-tailed godwit	NERC priority	High opportunity	-
Grasshopper warbler	NERC priority	High opportunity	-
Savi's warbler	NERC priority	High opportunity	-
Little bittern	Annex I	-	-
Little egret	Annex I	-	-
Great white egret	Annex I	-	-
Spoonbill	Annex I	-	-
Common crane	Annex I	-	-

Table 3.3 Risks and opportunities for wintering and passage waterbirds associated with freshwater and brackish wetlands. All were assessed using the full framework, based on bioclimate modelling carried out as part of the CHAINSPAN project.

Species	**Results of risks & opportunities assessment**
Greylag goose	High risk
Mallard	High risk
Pochard	High risk
Bewick's swan	Medium risk
Coot	Medium risk
Cormorant	Medium risk
Gadwall	Medium risk
Goosander	Medium risk
Great-crested grebe	Medium risk
Little grebe	Medium risk
Tufted duck	Medium risk
Whooper swan	Medium risk
Wigeon	Medium risk
Goldeneye	Risks & opportunities
Ferruginous duck	Limited impact
Pintail	Limited impact
Green sandpiper	Low opportunity
Lapwing	Medium opportunity
Pink-footed goose	Medium opportunity
Curlew	High opportunity
Golden plover	High opportunity
Great white egret	High opportunity
Little egret	High opportunity
Red-crested pochard	High opportunity
Shoveler	High opportunity
Snipe	High opportunity
Teal	High opportunity

Most lowland wetlands in the UK which are of high conservation value for their wetland birds are highly manipulated. Hence, there is potential to adapt management of these sites to reduce climate change and non-climate change-related pressures on species predicted to be at risk from climate change, and to provide suitable conditions for species for which the climate is predicted to become more suitable.

There are three main ways by which climate change is predicted to affect the quantity and quality of lowland wetland habitat, and for which it is possible to mitigate the negative impacts.

1. Rises in sea levels and possible increased storminess are predicted to result in increased coastal flooding causing saline inundation and eventual loss of coastal freshwater wetlands. This impact is not taken into account in the modelling of the impacts of climate change on species. It is an especially important issue for bitterns (high opportunity or limited impact) and other birds associated with freshwater reedbeds, since a high proportion of the UK's large freshwater reedbeds are in coastal areas and at risk of coastal flooding (Gilbert *et al.* 2010, Brown *et al.* 2012). The impacts of increased coastal flooding and eventual loss of coastal freshwater reedbeds can be mitigated by providing replacement freshwater reedbed in areas safe from coastal flooding (Sills & Hirons 2011, Brown *et al.* 2012).

2. Climate change is projected to result in changes in water availability, especially an increase in the rate of drawdown in water levels in spring in eastern and south-eastern England, and an increase in the frequency and severity of extreme rainfall and drought events. An increased rate of drawdown in water levels is predicted to be damaging for breeding lapwings (high risk), black-tailed godwits (high opportunity) and other lowland wet grassland breeding waders. This is because optimal conditions for breeding waders require only a relatively small rate of drawdown of water levels during their breeding season (Ausden *et al.* 2001, Ausden & Bolton 2012). A high rate of drawdown of water levels (and spring drought) can also be damaging for bitterns and also for colonial herons, egrets and spoonbills when nesting in wet reedbeds (although these colonial species also nest in trees, and wet scrub), because falling water levels can expose their nests to ground predators. Extreme rainfall events can also destroy wader nests (Green *et al.* 1987, Ratcliffe *et al.* 2005), and those of bitterns and 'ground-nesting' colonial waterbirds.

There is a range of hydrological methods that can be used to reduce the rate of drying out of wetlands in spring and early summer due to reductions in water availability. Measures for increasing water availability in spring and early summer have included securing additional inputs of water, and using reservoirs to store water abstracted from rivers in winter (when river flows are high) for use in spring and early summer. Measures to make best use of the available water on lowland wet grassland include reducing leaks from sluices and bunds; excavating shallow 'foot drains' to maintain wet areas when the rest of the field surface has dried out (Eglington *et al*. 2008); and rotationally flooding different areas of grassland instead of trying to keep a larger area of grassland flooded every year. It is also important to ensure that there is suitable infrastructure (e.g. pump capacity) to move sufficient quantities of water to areas which require it, and to remove excess water during extreme flood events.

An alternative approach, which could be adopted at some sites, would be to *accept* a greater rate of drawdown in water levels in spring and summer on wet grasslands in the future, but maintain higher water levels at the end of the winter, or in floodplain grasslands design and manage sites so that they are flooded with river water. This change in hydrology regime would be more in line with the changes in hydrology expected to occur as a result of climate change (more extensive and deeper flooding in winter caused by higher rainfall and a greater frequency of extreme rainfall events, and an increased rate of drawdown of water levels in spring and early summer caused by lower rainfall and higher evapotranspiration). This regime could make sites more attractive to some of the potential colonists, by creating more shallow floodwaters in spring and early summer for egrets, spoonbills and other potential colonists to feed in. It will probably not be optimal for breeding waders, but could be the most realistic option for providing suitable habitat for them. Further information on measures to address changes in water availability is provided by Ausden *et al.* (2011).

3. Projected reductions in summer rainfall and higher temperatures are predicted to increase the impacts of eutrophication (e.g. Mooij 2005). Increased algal blooms resulting from eutrophication could have negative impacts on birds which hunt visually in shallow water (bittern, egrets and herons), and on wildfowl species which feed mainly on submerged plants whose abundance is reduced by eutrophication (such as gadwall, pochard, red-crested pochard and coot: Cramp 1977). Red-crested pochard (high opportunity) specialises in feeding on stoneworts (Ruiters *et al.* 1994), which are particularly sensitive to the impacts of eutrophication. The most effective way to reduce eutrophication is to reduce concentrations of fertiliser runoff in inputs of water to wetlands. Agri-environment schemes and the Water Framework Directive have an important role to pay in reducing the impacts of eutrophication.

Lapwings (high risk) and black-tailed godwit (high opportunity) are both vulnerable to the impacts of foxes on their nests and possibly chicks (Teunissen *et al.* 2008, Ausden *et al.* 2009). Exclusion of, and killing of, foxes can be used to increase nesting success and probably breeding productivity in situations where the habitat is otherwise suitable (Bolton *et al.* 2007, Malpas *et al.* 2013).

Although a high proportion of wetland birds have been assessed as having a medium or high opportunity from climate change, five out of eight of these were assessed as likely to have their expansion limited by lack of suitable habitat, based on their current habitat requirements in the UK and elsewhere in Northwest Europe. These comprised bittern (requires large area of wet reedbed and open water: Tyler *et al.* 1998, Gilbert *et al.* 2005), purple heron (requires large areas of wetland habitat and safe, undisturbed nest sites: van der Hut *et al.* 2008) avocet (breeds mainly at saline lagoons); black-tailed godwit (mainly breeds on washlands and large, open areas of mainly peat lowland wet grassland with a high water table: Ausden & Bolton 2012); and Savi's warbler (associated with large reedbeds that contain an understory of litter, sedges and other vegetation: Bibby & Lunn 1982, van der Hut 1986, Neto 2006). Species whose expansion of their breeding population in the UK is likely to be severely limited by lack of suitable habitat also include the additional Annex I species of colonial waterbird which appear to be colonising the UK as breeding species, or which might begin regularly breeding in the future: spoonbill, great white egret, and night-heron, as well as common crane (which requires large areas of high quality wetland habitat with safe nesting areas: Stanbury 2011), The colonial species are all noted as being shy and sensitive to human disturbance during the breeding season (e.g. Fasola & Alieri 1992, Voslamber 1994, Voskamp & Zoetebier 1999), and require very large areas of wetland to sustain significant-sized breeding colonies (e.g. Platteeuw *et al.* 2010). More information on the area and habitat requirements of the colonial waterbirds shown in Table 3.2, together with those of other potential colonial-nesting colonists, is provided by Ausden *et al.* (2011).

There is also likely to be little suitable breeding habitat for another potential colonist - Kentish plover. Kentish plovers are vulnerable to the impacts of human disturbance and mammalian predators, especially when nesting on their seemingly preferred habitats of sandy beaches and unvegetated shingle (their main current or former breeding habitats in much in north-west Europe: Fojt *et al*. 2000, Meininger *et al.* 2007, Debout 2009). Brackish wetland nature reserves with no human disturbance and low impacts of mammalian predators might be the only suitable areas for them to breed in the UK, but again there is currently very little of this habitat in the UK.

In conclusion, while the results of the assessment suggest that a high proportion of bird species which breed in lowland freshwater and brackish wetlands in the UK are likely to face opportunities from a changing climate, these potential opportunities are likely to be limited unless significant areas of new wetland habitat are created. The UK is expected to remain important for its wintering and passage populations of waterbirds, although changes in climate will inevitably increasingly change the assemblage of wintering and passage waterbirds at individual sites.

Intertidal habitat

Of the wintering and passage birds associated with intertidal habitat which were assessed, a far higher proportion were considered to be likely to face opportunities from the impacts of climate change in the UK, than were considered to be at risk (Table 3.4). It is important to note, though, that projected increases in numbers of species at sites cannot take into account potential declines in the breeding range of many which breed in the Arctic and sub-Arctic (e.g. Lindström & Agrell 1999, Rehfisch & Crick 2003).

Table 3.4 Risks and opportunities for wintering and passage waterbirds associated with intertidal habitat. All were assessed using the full framework, based on bioclimate modelling carried out as part of the CHAINSPAN project

Species	Results of risks & opportunities assessment
Bar-tailed godwit	Medium risk
Wigeon	Medium risk
Oystercatcher	Risks & opportunities
Purple sandpiper	Risks & opportunities
Pintail	Limited impact
Redshank	Limited impact
Whimbrel	Low opportunity
Dunlin	Medium opportunity
Knot	Medium opportunity
Pink-footed goose	Medium opportunity
Ringed plover	Medium opportunity
Turnstone	Medium opportunity
Avocet	High opportunity
Black-tailed godwit	High opportunity
Dark-bellied brent goose	High opportunity
Curlew	High opportunity
Greenshank	High opportunity
Grey plover	High opportunity
Little egret	High opportunity
Sanderling	High opportunity
Shelduck	High opportunity
Teal	High opportunity

Importantly, the results of the bioclimate modelling do not take into account the fact that the total area of intertidal habitat in the UK is predicted to decline as a result of coastal squeeze (e.g. Brown *et al.* 2012). Therefore, potential opportunities are only likely to be fully realised, and risks minimised, if intertidal habitat lost through coastal squeeze (and through any port development or tidal barrages) is replaced through managed realignment or regulated tidal exchange (e.g. Atkinson *et al.* 2004, Mander *et al.* 2007). Population-level impacts on mollusc-feeding waterbirds (especially shelduck, oystercatcher and knot) caused by the loss of intertidal habitat due to climate change, could possibly be reduced by improving the feeding conditions on other areas of intertidal habitat, where the carrying capacity for these species has been reduced by unsustainable shellfisheries (Piersma *et al.* 2001, Stillman *et al.* 2001, Atkinson *et al.* 2010).

Lowland heathland

The majority of species associated with lowland heathland which were assessed using the framework were considered likely to face opportunity from climate change, the exception being tree pipit (Table 3.5). This result is unsurprising, given that these are mainly species with a southerly distribution in Europe, and which are towards the northern limit of their range in the UK. All of the species assessed, again with the exception of tree pipit, have been shown to be vulnerable to the impacts of human disturbance during the breeding season (including egg-collecting in the case of red-backed shrike) (Liley & Clarke 2003, Thirion & Lebon 2006, Tryjanowski *et al.* 2006, Mallord *et al.* 2007a & 2007b, Murison *et al.* 2007, Langston *et al.* 2007,Taylor *et al.* 2007), and so projected increases in distribution of these species could be limited by human disturbance.

Table 3.5 Risks and opportunities for SPA and NERC priority bird species breeding on lowland heathland. For SPA species, we have listed all Annex I species which currently breed in England (even if they do not have SPAs currently classified for them). See Table 3.2 for notes

Species	**Status**	**Results of risks & opportunities assessment**	
		Full framework	**Full framework (CHAINSPAN)**
Tree pipit	NERC priority	High risk	-
Tawny pipit	Annex I potential colonist		Low opportunity
Woodlark	Annex I & NERC priority	High opportunity	High opportunity
Nightjar	Annex I & NERC priority	High opportunity	High opportunity
Dartford warbler	Annex I	-	High opportunity
Red-backed Shrike	Annex I potential re-colonist	High opportunity	High opportunity

All of the species assessed as likely to face opportunities from the impacts of climate change are considered to have potential future increases in population/distribution limited by the availability of lowland heathland habitat, although there is a high likelihood that Dartford warbler and nightjar could breed in upland areas under a warmer climate. Apparently structurally suitable habitat for Dartford warbler and nightjar occurs at higher altitudes than these species currently occupy in the UK (upland heath with scattered trees and clearfells in the case of nightjar, and areas of tall heather and gorse on upland heath in the case of

Dartford warbler). Dartford warbler has already been increasing its altitudinal range in the UK in recent decades (Wotton *et al.* 2009, Bradbury *et al.* 2011). The most effective method for re-creating lowland heathland to facilitate northward range expansion of most of these lowland heathland species to expand their breeding range is through removal (or not re-planting) of conifers on ex-heathland, and creating heathland on former mineral extraction sites (Walker *et al.* 2004, Allison & Ausden 2006, Ausden *et al.* 2010, www.afterminerals.com). Converting forestry plantation to heathland results in a net increase in the global warming potential of greenhouse gas emissions, but the estimated increase per unit area is small compared to changes in the global warming potential of greenhouse gas emissions from other changes in land-use (Warner, 2008 & 2011). Control of public access (including restrictions on dogs) (e.g. Underhill-Day & Liley 2007) are likely to be required to provide optimal conditions for successful breeding.

The nearest current, and former, breeding habitat for tawny pipit (a potential colonist) in the Netherlands and Western France comprises coastal and inland sand dunes, where this species is considered highly vulnerable to human disturbance during the breeding season (Bijlsma 1990, Thirion & Lebon 2006). It is possible that suitable sandy conditions for breeding tawny pipits could potentially develop in the UK under a warmer and drier summer climate, although the suitability of coastal sand dunes in the UK for breeding tawny pipits is likely to be limited by human disturbance.

Lowland farmland

The majority of species associated with lowland farmland which were assessed were NERC priority species for which climate change was assessed as having little impact (Table 3.6). These are mainly species with a widespread breeding distribution in Europe. Eglington and Pearce-Higgins (2012) retrodicted population trends of farmland birds, and found that for grey partridge, turtle dove, skylark, yellow wagtail, starling, linnet, corn bunting and yellowhammer, changes in farming intensity had a far greater power in explaining population trends than retrodictions based only on weather. For these species, continuing implementing suitable agri-environment scheme prescriptions aimed at mitigating the impacts of agricultural intensification on farmland bird populations will continue to be crucial in maintaining (and potentially increasing) populations of these species. Grey partridge, lapwing and cuckoo were assessed as being at high risk, and yellowhammer at medium risk. Agri-environment prescriptions already exist for lapwing, grey partridge and yellowhammer (Vickery *et al.* 2004), but no agri-environment measures have been developed to benefit cuckoo, and research is required to fully diagnose the causes of decline before these can be developed.

There are three farmland species which currently regularly breed in the UK (corncrake, stone-curlew and cirl bunting) which were assessed as being likely to benefit from the impacts of climate change. These are all species whose UK breeding populations are currently largely dependent on conservation interventions: cirl bunting (maintenance and promotion of mixed farming through agri-environment prescriptions: Aebischer *et al.* 2000, Peach *et al.* 2001); stone-curlew (provision of nesting plots through agri-environment prescriptions plus interventions to reduce nest loss by two dedicated teams, together with conservation efforts on non-farmed habitats: Aebischer *et al.* 2000); corncrake (promotion of early cover and corncrake-friendly late mowing through agri-environment prescriptions, together with conservation interventions on nature reserves which support a significant proportion of the UK breeding population: Aebischer *et al.* 2000, O'Brien *et al.* 2006). The UK breeding populations of these three species have increased during the period assessed undoubtedly mainly due to conservation interventions (rather than due to climatic conditions), probably resulting in an over-assessment of their likely opportunities from climate change. Even though suitable habitat conditions could become more widespread for these species in the UK under a warmer climate, all three are likely to remain dependent on implementation of bespoke agri-environment prescriptions and conservation interventions in the foreseeable future.

Table 3.6 Risks and opportunities for SPA and NERC priority bird species associated with lowland farmland. We have included the Annex I Montagu's harrier, even though it does not have any SPAs classified for it. See Table 3.2 for notes

Species	**Status**	**Results of risks & opportunities assessment**	
		Full framework	**Full framework (CHAINSPAN)**
Grey partridge	NERC priority	High risk	
Lapwing	NERC priority	High risk	
Cuckoo	NERC priority	High risk	
Yellowhammer	NERC priority	Medium risk	
Turtle dove	NERC priority	Limited impact	
Yellow wagtail	NERC priority	Limited impact	
Skylark	NERC priority	Limited impact	
Song thrush	NERC priority	Limited impact	
Starling	NERC priority	Limited impact	
Dunnock	NERC priority	Limited impact	
Tree sparrow	NERC priority	Limited impact	
House sparrow	NERC priority	Limited impact	
Bullfinch	NERC priority	Limited impact	
Linnet	NERC priority	Limited impact	
Reed bunting	NERC priority	Limited impact	
Corn bunting	NERC priority	Limited impact	
Montagu's harrier	Annex I	Risk & opportunities	
Ortolan bunting	Annex I potential colonist		Medium opportunity
Stone-curlew	Annex I	Medium opportunity	High opportunity
Corncrake	NERC priority	High opportunity	High opportunity
Little bustard	Annex I potential colonist		High opportunity
Red-backed shrike	Annex I potential re-colonist		High opportunity
Cirl bunting	NERC priority	High opportunity	High opportunity

There are two farmland species shown in Table 2.2, for which the UK is predicted to potentially become climatically suitable for regular breeding (little bustard and ortolan bunting) plus a further species (red-backed shrike) which was assessed as likely to re-commence regular breeding in the UK. On farmland in Western and North-western Europe, all three of these species are associated with low-input, extensive agriculture (Salamolard &

Moreau 1999, Wolff *et al.* 2001 & 2002, Golawski *et al.* 2002, Vanhinsbergh & Evans 2002, Brambilla *et al.* 2007, 2009 & 2010, Berg 2008, Golawski & Golawski 2008). In southern Europe, Ortolan buntings also breed in hilly and rocky areas, especially containing burnt and bare ground (Brotons *et al.* 2008, Fonderflick *et al.* 2005, Menz *et al.* 2009, de Groot *et al.* 2010). There is therefore likely to be little or no suitable habitat for these species to breed on farmland in the UK, unless agri-environment schemes help support maintenance or creation of extensively managed agriculture. If these species did establish regular breeding populations in England in the future, then they might be largely, or completely, restricted to nature reserves.

In conclusion, for the majority of farmland species assessed, delivery of agri-environment schemes and in some cases additional direct conservation interventions, are predicted to be far more important than climate change in affecting their future population status in England.

Upland heath, blanket bog & in-bye

Of the species assessed, which are currently associated with upland heath and associated habitats, virtually all were assessed as being at high risk from climate change (Table 3.7). This is not surprising, given that the majority of these are species with a northern distribution in Europe, and for which the UK, is towards the southern edge of their breeding distribution. This is the opposite of the situation for lowland heathland. The only two species shown in Table 3.7, for which climate change was assessed as having likely opportunities are Dartford warbler and nightjar. These are both currently predominantly lowland species in the UK, but could potentially begin breeding in upland habitat in the UK under a warmer climate (see earlier). Hence, in order to help maintain the UK's internationally important assemblages of upland birds (Thompson *et al.* 2005), the main focus should be to implement management aimed at increasing the populations of high risk species, and reduce other climate change and non-climate change-related pressures on them.

There is good evidence of the success of interventions to benefit high risk species such as red grouse (high risk), black grouse (medium risk) and many upland breeding waders. Interventions to benefit red grouse involve rotational heather burning and legal control of generalist predators (e.g. Watson & Moss 2008). Measures to benefit black grouse include temporary reduction in grazing pressure and legal control of generalist predators (e.g. Baines 1996, Calladine *et al.* 2002, Grant *et al.* 2009).

For upland-breeding waders, there is evidence that densities of a range of species is reduced by moorland fragmentation and edge-effects associated with commercial conifer plantations (Pearce-Higgins *et al.* 2009), and that densities of breeding dunlin are lower close to conifer plantations (Hancock *et al.* 2009). Declines in numbers of upland-breeding breeding golden plovers, curlew and snipe have been associated with local exposure to forest edge (Amar *et al.* 2011a, Douglas *et al.* 2014). Hence, a key measure to benefit these species is avoidance of planting conifer plantations, and where possible removing them from inappropriate areas. There is also evidence that wader populations may be limited or declining as a result of increases in generalist predators, such as corvids and foxes (Parr *et al.* 1992, Grant *et al.* 1999, Tharme *et al.* 2001, Douglas *et al.* 2014). Legal control of generalist predators (especially foxes), where they are shown to have significant impacts on wader breeding productivity, and non-lethal methods have been exhausted, may significantly increase wader abundance (Fletcher *et al.* 2010).

Blocking of artificial drainage on blanket bog is predicted to improve food supply for golden plover (Pearce-Higgins 2010 & 2011, Pearce-Higgins *et al.* 2010, Carroll *et al.* 2011), and by raising the water table to a more natural state, is likely to also benefit dunlin, snipe and curlew, and make these populations more resilient to climate change.

Table 3.7 Risks and opportunities for SPA and NERC priority bird species associated with upland heath, blanket bog & in-bye. See Table 3.2 for notes

Species	**Status**	**Results of risks & opportunities assessment**	
		Full framework	**Full framework (CHAINSPAN)**
Hen harrier	Annex I & NERC priority	High risk	
Red grouse	NERC priority	High risk	
Lapwing	Part of upland SPA assemblage	High risk	
Dotterel	Annex I		High risk
Golden plover	Annex I	High risk	
Curlew	Part of upland SPA assemblage & NERC priority	High risk	High risk
Snipe	Part of upland SPA assemblage	High risk	
Dunlin	Part of upland SPA assemblage	High risk	
Cuckoo	NERC priority	High risk	
Short-eared owl	Annex I	High risk	
Whinchat	Part of upland SPA assemblage	High risk	
Wheatear	Part of upland SPA assemblage	High risk	
Ring ouzel	Part of upland SPA assemblage & NERC priority	High risk	
Twite	Part of upland SPA assemblage & NERC priority	High risk	
Peregrine	Annex I	Medium risk	
Merlin	Annex I	Medium risk	
Black grouse	Annex I & NERC priority	Medium risk	
Golden eagle	Annex I	Limited impact	
Oystercatcher	Part of upland SPA assemblage	Limited impact	
Redshank	Part of upland SPA assemblage	Limited impact	Limited impact
Nightjar	Annex I	High opportunity	High opportunity
Dartford warbler	Annex I	High opportunity	High opportunity

Populations of hen harriers and golden plovers which breed on upland heath will feed on surrounding agricultural land (Whittingham *et al.* 2000, Pearce-Higgins & Yalden, 2003, Amar & Redpath 2005, Amar *et al.* 2011a). Dunlins nesting on blanket bog will also feed on surrounding agricultural land. Providing suitable conditions for foraging on this agricultural land (rough grassland for hen harriers to hunt for small mammals and also birds, and earthworm- and tipulid-rich, traditionally-used agriculturally-unimproved pasture for golden plovers and dunlins) should also increase the resistance of these populations.

An additional pressure is the illegal killing and disturbance of SPA raptors. In particular, there is strong evidence that illegal persecution is preventing hen harriers from occupying large areas of otherwise suitable habitat, and there is also strong evidence of illegal persecution of peregrines on grouse moors (Amar *et al*. 2011b, Fielding *et al.* 2011). Illegal persecution of peregrines is also suspected to be limiting their breeding population in some upland areas of England.

Recreational disturbance has been cited as a pressure on a number of upland bird species, but generally is regarded as having only being of localised importance (Pearce-Higgins *et al.* 2009). In cases where disturbance may be limiting breeding success or distribution, then measures to manage people, for example through creating paved footpaths to direct visitors away from the most sensitive areas, may be successful (Finney *et al.* 2005).

There have not been any trials demonstrating successful interventions to benefit dotterel, short-eared owl, cuckoo, whinchat wheatear or ring ouzel (all high risk) in the UK. Trials are currently underway to improve habitat conditions for breeding twite (high risk). These are involving reseeding grassland with plant species, whose seeds are thought to be important food sources for twite. It is too early to assess the effectiveness of these trails.

Lowland broadleaved woodland

The species associated with lowland broadleaved woodland which were assessed, included a high proportion of species assessed as being at high risk of climate change-related decline. Many of these species are thought to have declined in recent decades as a result of changes in woodland structure, caused by the abandonment of woodland management, and increased browsing of the woodland understory by deer (Symes & Currie 2005, Hewson *et al.* 2007, Holt *et al.* 2011, Newson *et al.* 2012).

Adaptive management of woodlands takes time, because of the period required for trees to mature, and consequently the long timescales over which changes in woodland tree species composition take place. While considerable research has been invested in understanding habitat selection by most of the species assessed as being at medium or high risk of climate change-related decline (wood warbler, marsh tit, willow tit and spotted flycatcher: e.g. Hinsley *et al.* 2007, Stevens 2007, Lewis *et al.* 2009, Mallord *et al.* 2012), reasons for declines in populations of these species (as well as lesser redpoll: high risk) are still not clearly understood, and successful interventions for these species are yet to be demonstrated. Instead, current advice for benefitting these and other lowland broadleaved woodland bird species, is to create varied woodland structure, to counter-act the impacts of abandonment of management of lowland woodland, and management of deer populations to redevelop an understory and allow tree regeneration (Symes & Currie 2005). Providing greater structural diversity within woodland, a diverse mix of suitable native tree species, and increasing the size of individual woodlands (and for some species clusters of woodlands in close proximity) would appear to be the best strategy for helping ensuring the maintenance of suitable habitat conditions within lowland woodlands as a whole under uncertain future climates (Fuller *et al.* 2007, Kirby *et al*. 2009).

Table 3.8 Risks and opportunities for SPA and NERC priority bird species associated with lowland broadleaved woodland. See Table 3.2 for notes

Species	Status	Results of risks & opportunities assessment	
		Full framework	**Full framework (CHAINSPAN)**
Cuckoo	NERC priority	High risk	
Wood warbler	NERC priority	High risk	
Willow tit	NERC priority	High risk	
Marsh tit	NERC priority	High risk	
Lesser redpoll	NERC priority	High risk	
Spotted flycatcher	NERC priority	Medium risk	
Dunnock	NERC priority	Limited impact	
Song thrush	NERC priority	Limited impact	
Bullfinch	NERC priority	Limited impact	
Hawfinch	NERC priority	Medium opportunity	
Black woodpecker	Potential Annex I colonist		Moderate opportunity
Lesser-spotted woodpecker	NERC priority	High opportunity	

One species, black woodpecker, was assessed as potentially colonising the UK under future climatic conditions. In Northwest Europe, black woodpeckers are associated with large areas of old growth pine and beech woodland, (Tjernberg *et al.* 1993, Fernandez & Azkona 1996, Garmendia *et al.* 2006, van Manen 2012). Suitable habitat for black woodpeckers is likely to be limited in the UK, and colonisation of the UK by black woodpecker might be prevented by its poor dispersal ability.

Seabirds

Changes in the abundance of seabirds were modelled based on current and projected future climatic conditions. It is important to note that variables such as sea-surface temperature and ocean were not accounted for that may influence the abundance of the key prey species of seabirds (Arnott & Ruxton, 2002, Durant *et al.* 2003, Frederiksen *et al.* 2004 & 2006 Harris *et al.* 2008). We therefore need to be cautious about the assessments of seabirds, although the CHAINSPAN models used were able to predict recent population trends (Johnston *et al.* 2013). Of the seabirds assessed, approximately similar numbers of species were assessed as being at risk of climate change-related decline, as of being of medium or high likelihood of benefitting from the impacts of climate change (Table 3.9).

The nine species assessed as being at high or medium risk from climate change were dominated by northerly distributed, mainly cliff-nesting species, with four of these species feeding mainly on sandeels (Arctic tern, guillemot, puffin and kittiwake: Burthe *et al.* 2012, Frederiksen *et al.* 2006, Rindorf *et al.* 2000, Wanless *et al.* 2005). There is good evidence that the supply of sandeels for these species is strongly affected by a combination of sea surface temperatures and the impacts of commercial fishing (Frederiksen *et al.* 2004 & 2008). Therefore, a key way to mitigate projected negative impacts on the food supply of seabirds is to minimise pressures on these fish stocks from commercial fishing (Frederiksen *et al.* 2004). There is also the potential to provide new safe nesting islands for Sandwich terns (high risk), to enable then to exploit food resources at sites which currently lack suitable nesting sites.

Table 3.9 Risks and opportunities for SPA and NERC priority bird species associated with seabirds. See Table 3.2 for notes

Species	Status	Results of risks & opportunities assessment	
		Full framework	Full framework (CHAINSPAN)
Arctic tern	Annex I		High risk
Fulmar	Breeding seabird		High risk
Kittiwake	Breeding seabird		High risk
Sandwich tern	Annex I		High risk
Shag	Breeding seabird		High risk
Common gull	Breeding seabird		Medium risk
Guillemot	Breeding seabird		Medium risk
Puffin	Breeding seabird		Medium risk
Razorbill	Breeding seabird		Medium risk
Common tern	Annex I		Limited impact
Gannet	Breeding seabird		Limited impact
Great black-backed gull	Breeding seabird		Limited impact
Storm petrel	Annex I	Medium opportunity	
Herring gull	Breeding seabird		Medium opportunity
Little tern	Annex I		Medium opportunity
Black-headed gull	Breeding seabird		High opportunity
Cormorant	Breeding seabird		High opportunity
Lesser black-backed gull	Breeding seabird		High opportunity
Manx shearwater	Breeding seabird		High opportunity
Roseate tern	Annex I & NERC priority		High opportunity
Mediterranean gull	Annex I	High opportunity	

The nine species assessed as being likely to face opportunity from climate change comprised a mixture of species with a less northerly distributed breeding distribution in the UK, which have a variety of feeding strategies, and none of which feed mainly on sandeels. Little terns are likely to suffer the additional pressure of increased frequency of flooding of nests on beaches as a result of higher sea levels and possible increased storm events, factors which are not taken into account in the bioclimate modelling (Pickerill 2000, Ratcliffe *et al.* 2000, Fasola *et al.* 2002). Range expansion of little terns is likely to be limited by the availability of their main breeding habitat: beaches free from human disturbance, and sand or shingle islands free from mammalian predators (Pickerill 2000, Fasola *et al.* 2002). Mammalian predator-free islands for nesting little terns (as well as Sandwich terns, other seabirds and waders) can be created using dredgings (Allcorn 2003, Scarton 2008).

Range expansion of Manx shearwater and storm petrel is likely to be limited by the availability of rat-free nesting islands (Ratcliffe *et al.* 2009). It should therefore continue to be a priority to prevent colonisation by rats of islands holding important seabird colonies using suitable quarantine methods. It is also important to identify the presence of rats on important seabird nesting islands, and to eradicate them from important, or potentially important, seabird nesting islands. Absence of rats should also benefit puffins and terns. Priorities for eradication of rats on islands in the UK have been identified by Ratcliffe *et al.* (2009).

Conclusions

Of the breeding populations of SPA and NERC priority species assessed, 36 were considered to be at medium or high risk of decline from climate change, while 31 were considered to experience medium or high opportunities from climate change in England. For wintering populations, the respective figures were 15 and 21.

The majority of bird species assessed as being at medium or high risk of climate change-related decline are upland species, northern breeding seabirds, and a range of wintering waterbirds, mainly diving species. For the 36 breeding species assessed as being at high or medium risk of climate change-related decline, successful interventions to increase population size were identified for eight species, and species-specific measures which are likely to prove beneficial (but whose success has not yet been demonstrated) identified for a further nine. It is important to increase the resistance of species assessed as being at medium or high risk of climate change-related decline, both because of the uncertainty of the impacts of climate change on individual species, but also because even though a species might eventually be lost from a site, maintaining it in suitable condition can be important in providing emigrants to colonise other sites (Gilbert *et al.* 2010).

The majority of bird species assessed as being at medium or high likelihood of climate change-related increase in the UK were breeding wetland birds, species associated with lowland heathland, a variety of seabirds and wintering waterbirds, and several farmland birds. An important conclusion for breeding species assessed as being at medium or high likelihood of climate change-related increase, is that range expansion of 17 species is likely to be limited by lack of suitable habitat; that three species are currently heavily dependent on bespoke interventions. Many of the potential opportunities of climate change on England's bird fauna are therefore unlikely to be realised to any great extent in the absence of considerable habitat re-creation and restoration, while maintenance of the populations of many other species are likely to remain dependent on the delivery of beneficial agri-environment scheme prescriptions.

4 Using a decision framework to identify climate change adaptation actions for species of conservation concern

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Introduction

Climate change threatens biodiversity directly and by compounding other drivers of change arising from use of land and other resources (Brook *et al.* 2008). Many elements of principles that have been developed to guide adaptation for biodiversity are neither new nor specific to climate change and underpin existing conservation policy and practice (Hopkins *et al.* 2007; Smithers *et al.* 2008). However, the extent to which existing conservation actions identified nationally for Natural Environment and Rural Communities Act 2006 (NERC Act) species (Joint Nature Conservation Committee - JNCC UK species pages; http://jncc.defra.gov.uk) are matched to the threat of climate change has not been considered in detail.

In this study, we assessed the needs of 30 NERC Act species using a decision framework (Oliver *et al.* 2012) that is intended to promote integration of climate change adaptation principles into conservation planning by prioritizing and targeting relevant actions to increase the adaptive capacity of species. In doing so, the framework extends the prioritization 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 also reflects recent debate about the need to address existing threats to species before enhancing functional connectivity (Doerr *et al.* 2011; Hodgson *et al.* 2011).

The aim of our study was to compare how existing conservation actions identified nationally for NERC Act species (JNCC UK species pages; http://jncc.defra.gov.uk) differ from those keyed out using the decision framework.

Methods

Species selection
From the NERC Act 2006 priority species list, an initial long-list of 114 species was identified for which the Biological Records Centre held sufficient distribution data to calculate a trend over time in distribution extent (see Chapter 1 for methods). 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 10 species associated with each habitat type. One broadleaved woodland species was problematic and removed from analysis because there were two sub-species present in the north of Great Britain, 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 (i.e. 11 lowland heath-, 9 broadleaved woodland- and 10 calcareous grassland-associated species).

Climate envelope models

The same climate envelope models were used as those described earlier in this report (section 1 'Assessment of Risks and Opportunities'). There are of course 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 on UK data (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) and current distribution data may not be comprehensive, such that modelled climate space may appear narrower than the true climatic niche, 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).

In our analyses, we have done our best to deal with these issues. For example, we attempted to account for spatio-temporal variability in recorder effort (Chapter 1 of this report) and we did not simply use mean estimates of climate suitability but assessed the uncertainty bounds of estimated probabilities of occurrence (see below). Nevertheless, appropriate caution should be taken when using these in model outputs.

We used projections from the IPCC medium emission A1B scenario (equivalent to a 4ºC rise in global mean temperatures by 2080) which may be more realistic, given current emissions trajectories than the low emission B1 scenario (International Energy Agency 2012). For each species, we mapped current distribution, modelled current suitable climate space from the statistical model linking climate to occurrence, and projected future suitable climate space in 2070-2099 using the methods outlined in Chapter 1 of this report, based on that same model. We then mapped the difference in probabilities of occurrence between current and future suitable climate space, setting a minimum arbitrary threshold for a recognised change as 20% of the maximum modelled probability of occurrence in the historic period based on the model linking occurrence to climate (P_t). Existing presence records outside of the modelled current suitable climate space were also counted as currently occupied. This threshold was chosen in order to allow us to identify three climate zones for the purposes of this decision framework: a) Adversely Sensitive Areas (where the species was present with probability > P_t in the historic period, but then suffered a decrease in probability of magnitude greater than P_t); New Climate Space (where the species experienced an increase in probability of occurrence greater than P_t); c) Climate Overlap Areas (where the species was present with probability> P_t in the historic period and did not suffer declines or increases in probability of magnitude greater than P_t). Using an arbitrary threshold based on percentage change in maximum modelled probability of occurrence in the historic period rather than on an absolute percentage probability of occurrence was intended to better reflect uncertainties associated with the modelling.

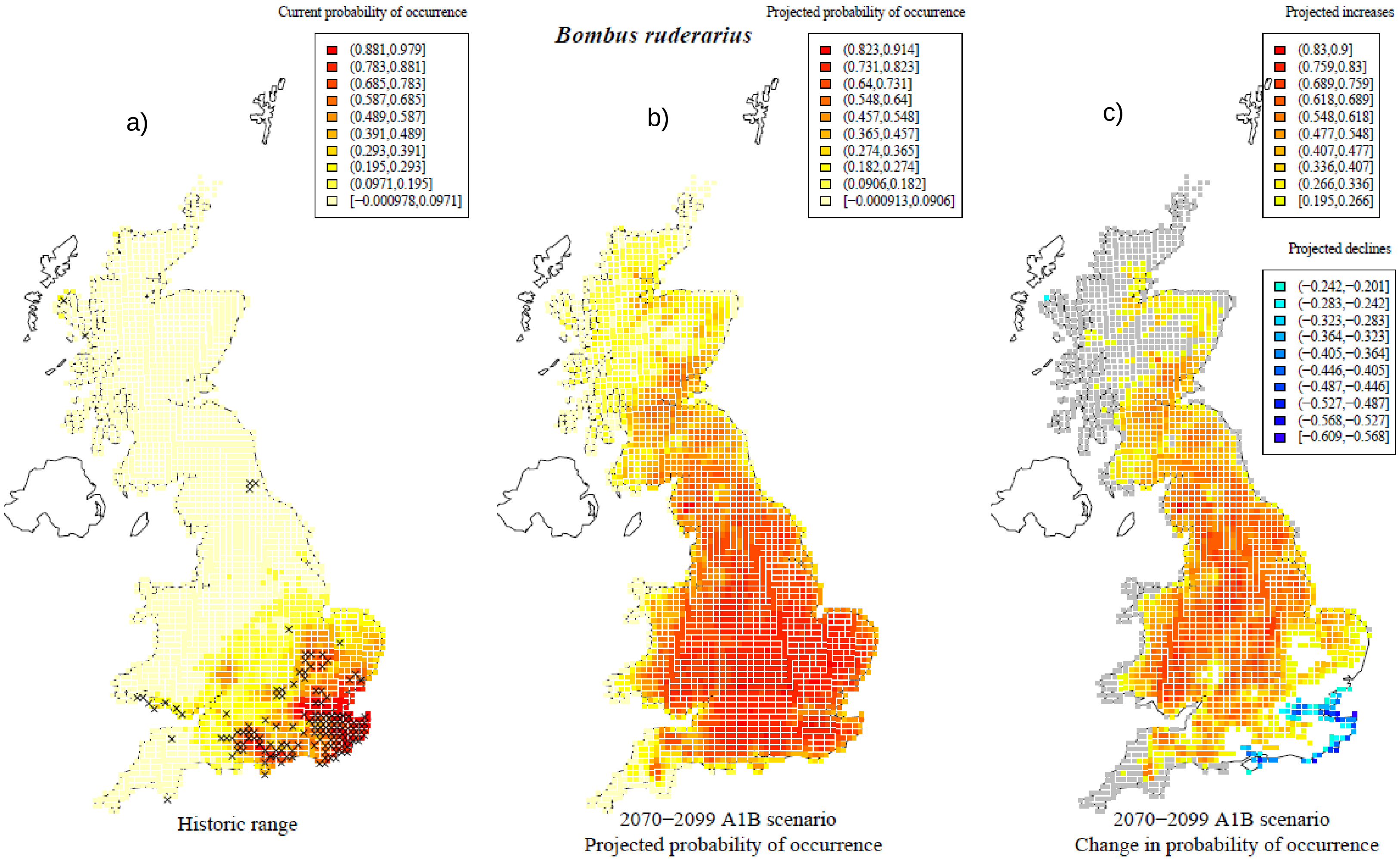

Figure 4.1 Maps showing a) historic distribution of an example species, *Bombus ruderarius.* Black crosses show submitted records, coloured squares show modelled probability of historic (1970-1990) occurrence; b) Projected probability of occurrence under A1B scenario; c) The change in modelled probability of occurrence coloured to delineate different climate 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

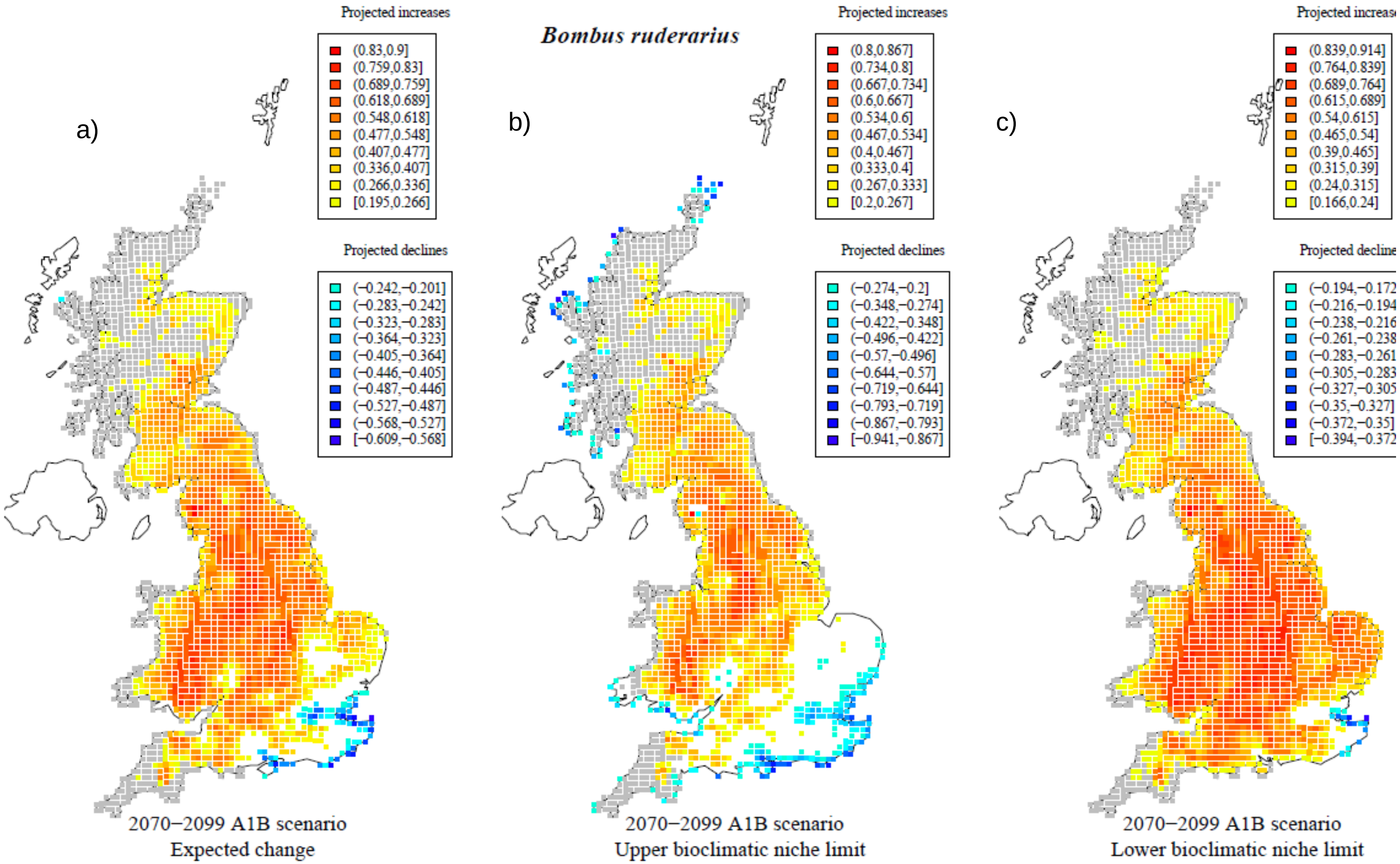

Figure 4.2 Maps showing a) Projected change in modelled probability of suitable climate space for *Bombus ruderarius* coloured to delineate different climate zones (the same as Figure 1c); b) and c) Projected future change in probability of suitable climate space for *Bombus ruderarius* in relation to the upper and lower 95% confidence intervals for the modelled historic probability of occurrence. Colours as in Figure 4.1

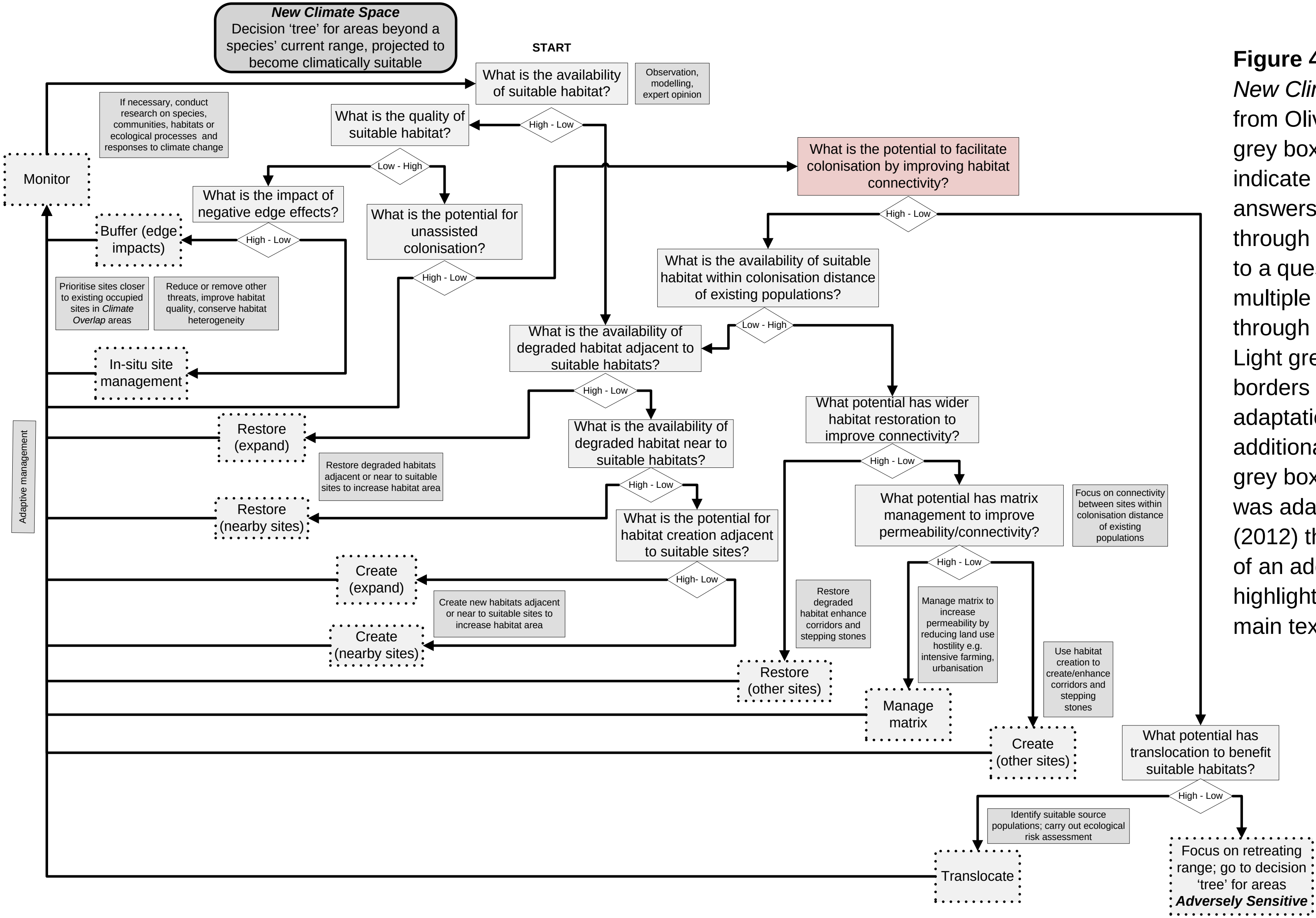

Figure 4.3 Decision tree for *New Climate Space* (adapted from Oliver *et al*. 2012). Light grey boxes with solid borders indicate questions whose answers lead to different routes through the tree. If the answer to a question is uncertain, then multiple routes should be through the tree simultaneously. Light grey boxes with dashed borders indicate suggested adaptation actions, with relevant additional information in dark grey boxes. The decision tree was adapted from Oliver *et al.* (2012) through the incorporation of an additional question box highlighted in red here (see main text for explanation).

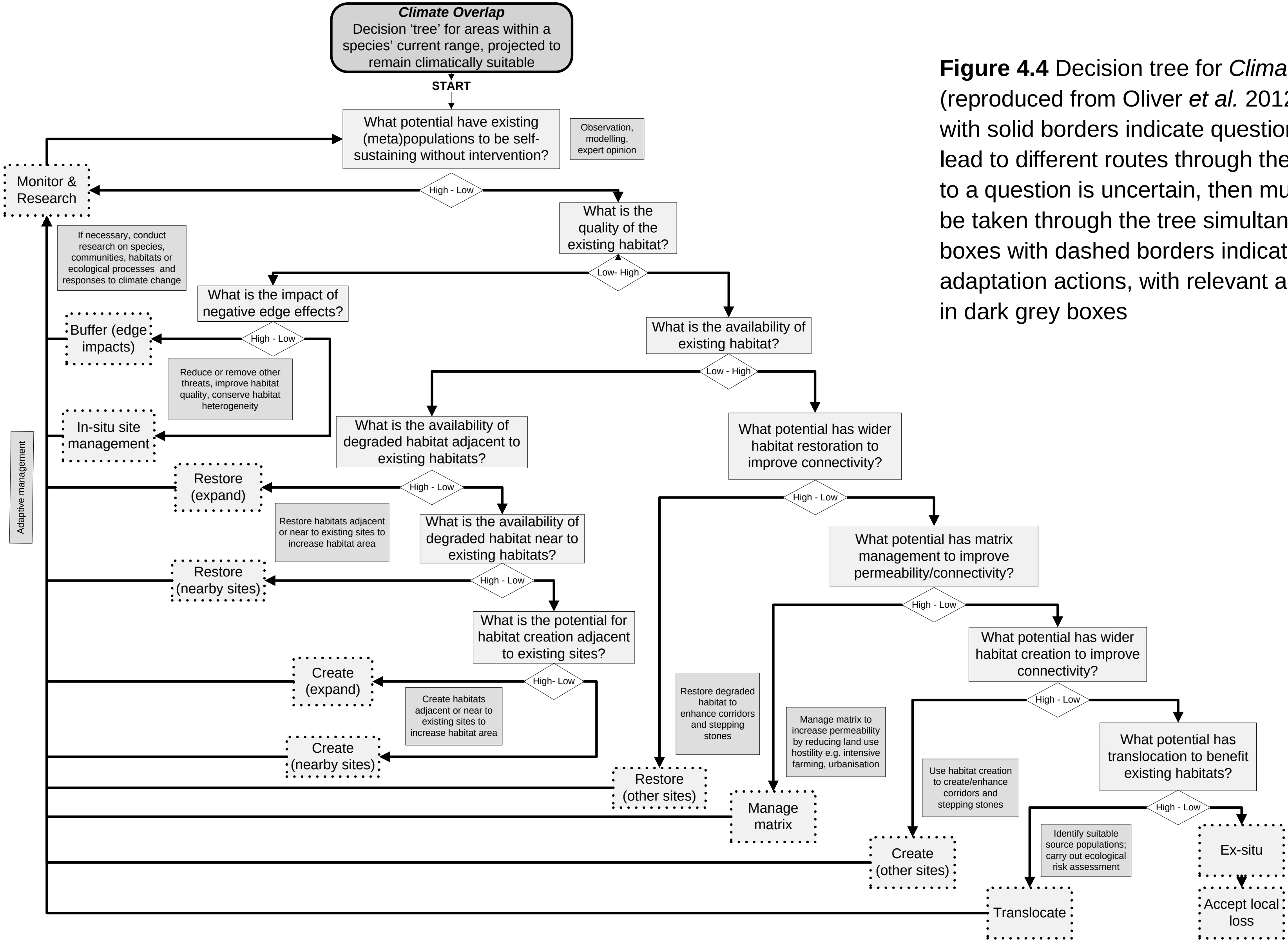

Figure 4.4 Decision tree for *Climate Overlap Areas* (reproduced from Oliver *et al.* 2012). Light grey boxes with solid borders indicate questions whose answers lead to different routes through the tree. If the answer to a question is uncertain, then multiple routes should be taken through the tree simultaneously. Light grey boxes with dashed borders indicate suggested adaptation actions, with relevant additional information in dark grey boxes

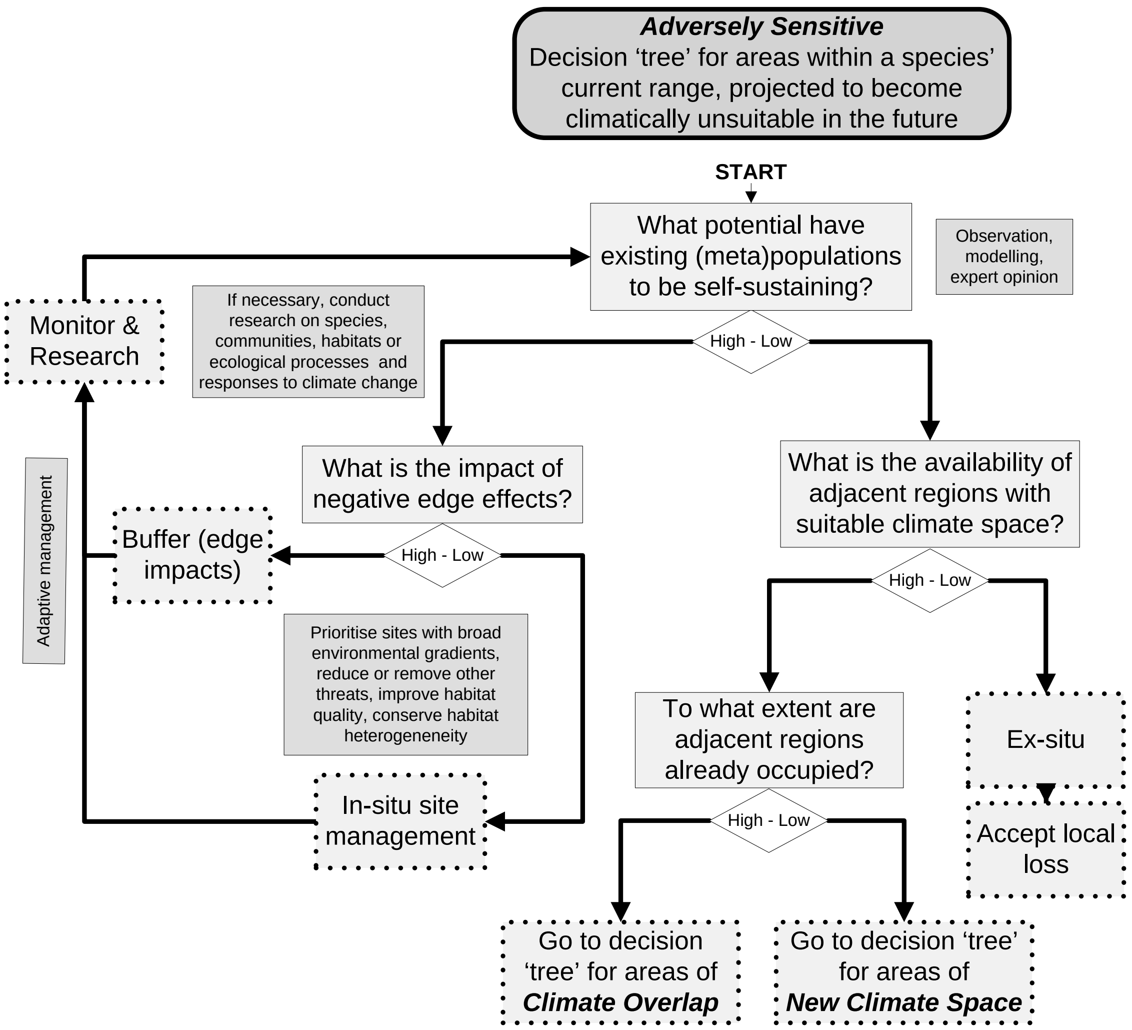

Figure 4.5 Decision tree for Adversely Sensitive Areas (reproduced from Oliver *et al.* 2012). Light grey boxes with solid borders indicate questions whose answers lead to different routes through the tree. If the answer to a question is uncertain, then multiple routes should be taken through the tree simultaneously. Light grey boxes with dashed borders indicate suggested adaptation actions, with relevant additional information in dark grey boxes

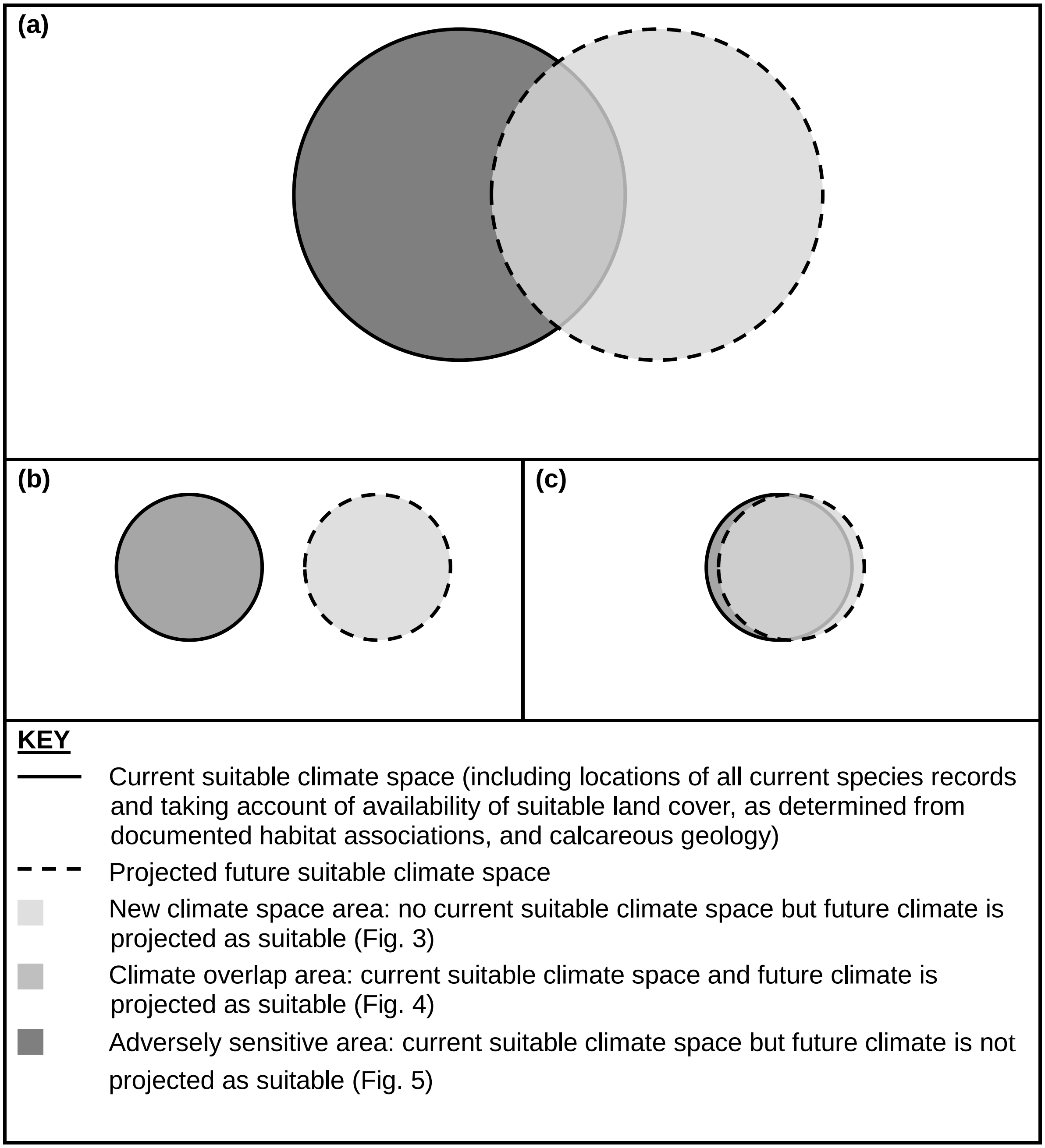

Figure 4.6 Use of the decision trees in relation to the spatial relations between a species' current and projected future suitable climate space (adapted from Oliver *et al.* 2012).

Figure 4.1 gives an example of these maps of suitable climate space and how future projections are used to delineate different climatic zones. In this case, for the species *Bombus ruderarius* the threshold value, P_t, 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 bioclimate models by taking the 95% confidence intervals of the modelled historic probability of occurrence, as the upper and lower limits of the bioclimatic niche, and repeating the process above; an example in shown in Figure 4.2. These maps were consulted in order to help address uncertainty in the delineation of climate overlap, new climate space and adversely sensitive areas.

Using the decision trees
As the framework is intended for use by conservation managers, we demonstrate its rapid deployment at a national scale by relying on readily accessible and easily interpreted sources of information (Table 4.1). For each of the three climate zones and for each species, we used the appropriate decision tree(s) to identify recommended climate change adaptation actions (Figures 4.3-4.5), as described in Oliver *et al.* (2012). 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 (Figure 4.6a). 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 4.6b), 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 4.6c).

Projections of future climate space were tempered by consideration of the availability of suitable land cover (as determined from documented habitat associations), 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. During the process of running the 30 species through the decision framework, we encountered an issue for species where new climate space was a very long distance from currently occupied areas. In these cases, there is little or no scope to facilitate colonisation by improving habitat connectivity before attempting translocation, which was the order of actions suggested by the original decision tree for new climate space areas. Our original motivation was to ensure that actions that are beneficial to a wide range of species and not just the focal species are given higher priority. However, in cases where there is clearly no way to facilitate colonisation by improving habitat connectivity, it makes no sense for the decision framework to promote such actions. Therefore, the original decision tree relating to new climate space areas was revised to include an additional question (what is the potential to facilitate colonisation by improving habitat connectivity?), which avoids this eventuality and, in appropriate circumstances where the availability of suitable high quality habitat is high, leads directly to consideration of translocation (Figure 4.3). Nevertheless, where the current availability of suitable habitat in new climate space is low, the decision tree prioritises restoring and creating habitat in new climate space and only then prioritises translocation when running through the decision tree a second time. This highlights the general importance of running through the decision framework iteratively (as described in Oliver *et al.* 2012), to identify a full prioritised list of adaptation actions. This then facilitates consideration of socioeconomic, political and practical issues associated with implementing co-dependent bundles of actions, upon which it is acknowledged that successful implementation will ultimately depend.

Table 4.1 Sources of information used to answer questions in the decision framework

Data source	Details
1	Trends in species distribution extent from 1970-2009 using mixed models approach (see Chapter 1 of this report 'Assessment of Risks and Opportunities')
2	Climate envelope maps (see section 1 of this report 'Assessment of Risks and Opportunities')
3	JNCC UK species pages: http://jncc.defra.gov.uk
4	Webb, J.R., Drewitt, A.L., & Measures, G.H., 2010. Managing for species: Integrating the needs of England's priority species into habitat management. Part 1 Report. *Natural England Research Reports, Number 024*: 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/

Comparing recommended conservation/ adaptation actions

We compared adaptation actions identified by the decision framework in different climate zones to current conservation actions recommended for each of the species (JNCC UK species pages; http://jncc.defra.gov.uk). In some cases, the location of conservation actions is 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 is not (e.g. "Develop large-scale landscape processes and mechanisms that will support and encourage the evolution currently operating in this genus"). However, we have assumed that this infers these actions are 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 recommends monitoring to find new populations of a species. In this case, we assumed this action is intended to occur in all three climate zones.

To compare actions, we produced frequency plots of existing conservation recommendations versus the adaptation actions keyed out using the decision framework across the three climate zones. We also compared adaptation actions identified by the decision framework across the three habitat types.

Results

For each species, tables describing how each question in the decision framework was answered along with supporting evidence can be found in supplementary files accompanying this report (labelled Adaptation Framework Results_Broadleaved Woodland species.xls; Adaptation Framework Results_ Chalk Grassland species.xls; Adaptation Framework Results_ Lowland Heath species.xls). Accompanying maps used to delineate the climatic zones for each species (see methods above) can be found in supplementary files (Folders: 'map_projected3' and 'maps_uncertainty')[1].

Comparison between JNCC's existing conservation recommendations and adaptation actions identified by the decision framework
A summary of recommended conservation and adaptation actions stratified by climatic zone for all 30 species is shown in Figure 4.7.

There were a number of **similarities** between the recommendations:

1. The need for 'monitoring and research'; in many cases not a lot is known about species' current status, their habitat requirements or the relative importance of different threats to species.
2. The need for 'in-situ management'; addressing other threats not linked to climate increases species' resilience and may promote colonisation and propagule pressure.

However, there were also a number of key **differences:**

1. 'Buffer edge impacts' is often identified by the decision framework but not as a JNCC conservation action. Where species populations and their habitats are small and highly fragmented, it may be an important first step in reducing other threats not linked to climate change.
2. JNCC actions are focused almost exclusively within species' existing ranges (i.e. in areas of climate overlap or that are adversely sensitive). In contrast, the decision framework identifies a range of actions in areas of projected new climate space, including 'buffer edge impacts', 'in-situ management', 'restore/create habitat' and 'translocate'.

[1] The file names are labelled with species codes which can be found in cell B1 of the Adaptation Framework results spreadsheets for each species.

3. In adversely sensitive areas, the decision framework identifies fewer actions than are recommended by JNCC, including ‘accept local loss’, which is never recommended 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, 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. It is however the case that priority should be given to maintaining populations in places with the best long term chance of persistence.
4. There are some differences in the balance of actions within climate overlap areas. For example, whilst the decision framework often identifies ‘buffer edge impacts’, JNCC places greater emphasis on ‘manage matrix’ and does not explicitly consider the need to buffer habitats.

Comparison between climate change adaptation actions across habitat types
Species-habitat associations were determined from Webb *et al.* 2010 (see Methods). However, it should be noted that, in addition to lowland heath, broadleaved woodland or calcareous grassland, a number of species are also listed as being associated with other habitats (e.g. lowland farmland). There were some minor differences in the balance of actions between habitat types (Figure 8). For example, 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 to a lesser degree on restoration and habitat creation in the wider landscape. In all habitats, translocation of plant species was occasionally recommended as a possible option in new climate space, as was accepting loss of some populations in adversely sensitive regions.

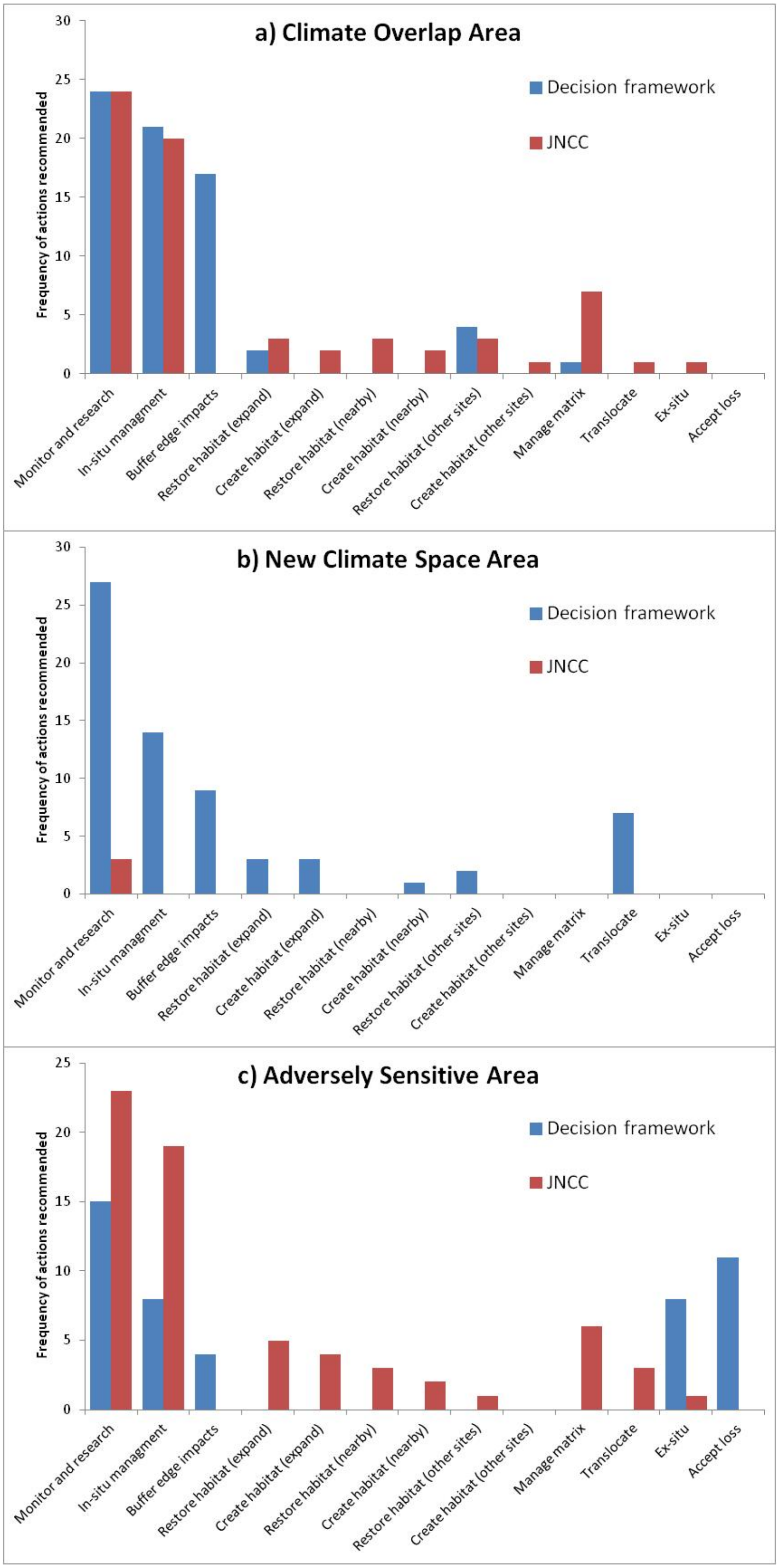

Figure 4.7 Frequency of conservation actions recommended for 30 NERC Act species by JNCC compared to those identified by the climate change decision framework. Actions are ascribed to areas of each species' projected climate space (panels a, b and c).

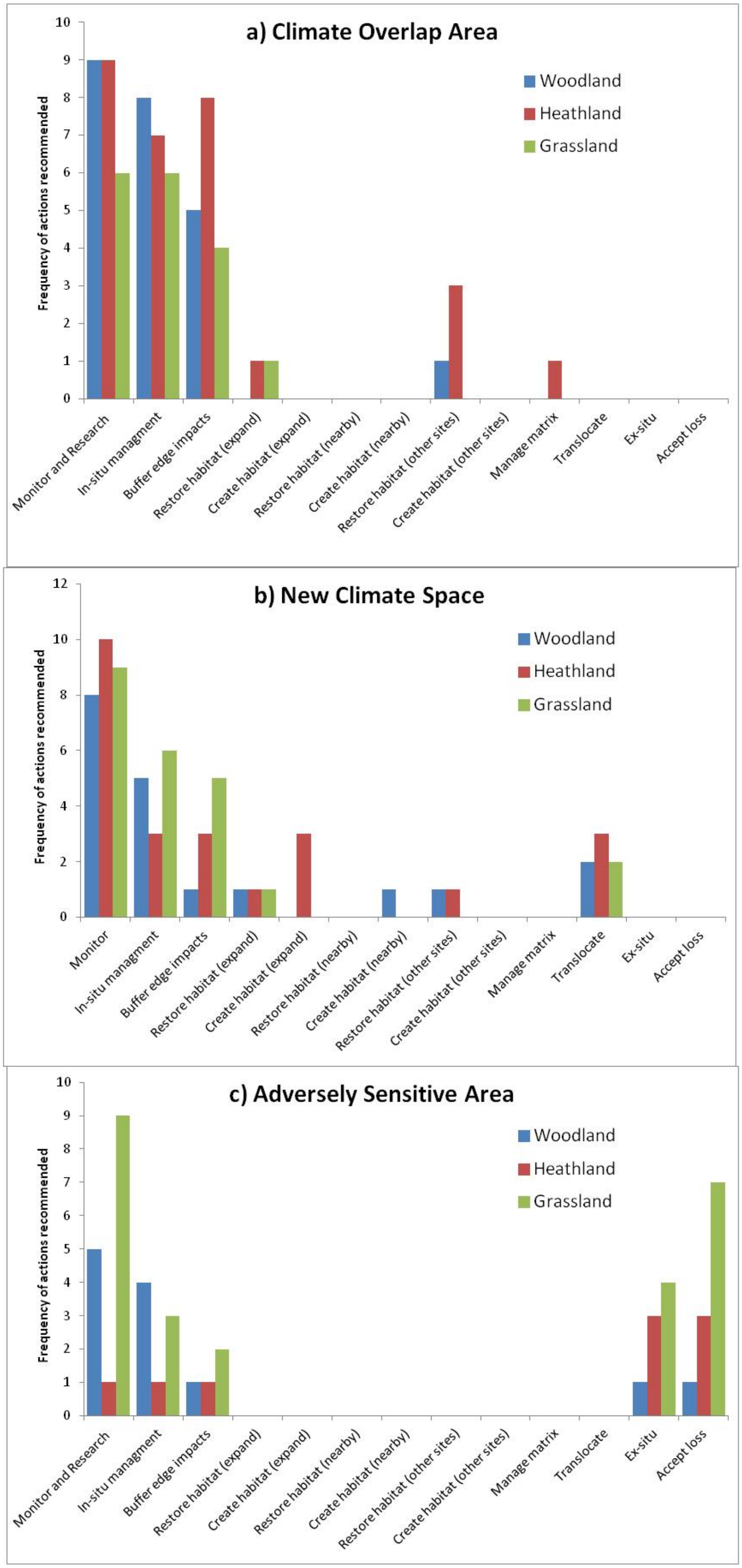

Figure 4.8 Frequency of climate change adaptation actions recommended by the decision framework for 30 species with different habitat associations. Actions are ascribed to areas of each species' projected climate space (panels a, b and c)

Discussion

Our comparison of climate change actions recommended from the decision framework (Oliver *et al.* 2012) with existing conservation recommendations (JNCC UK species pages; http://jncc.defra.gov.uk) found a number of similarities. The first is that both highlight a pressing need for monitoring and research. In many cases not a lot is known about species' current status, their habitat requirements or the relative importance of different threats to species. Second, both sets of actions identify the importance of in-situ management within species' historic ranges. Such similarities are to be expected to some extent because addressing other threats not linked to climate also increases species' resilience to climate changes and may promote colonisation and propagule pressure.

However, our comparison also revealed key differences betwen the balance of actions and in where actions should be carried out. For example, the decision framework identifies the need for effort in areas of potential new climate space and places less emphasis than JNCC on actions in adversely sensitive areas, wherever there are no adjacent regions with suitable climate space. This reflects the recognition of the dynamic nature of species' climate space and the consequent need for a dyamic approach to nature conservation (Smithers *et al.* 2008). For example, management, restoration and creation of habitats beyond species' current ranges and even translocation may be necessary to facilitate species' range shifts (Hoegh-Guldberg *et al.* 2008). Similarly, an increased focus on actions outside of adversely sensitive areas under 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.

In using the decision framework to identify and prioritise actions, the uncertainty in climate space projections must be taken into account. 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 suggests accepting loss of species populations within adversely sensitive areas where there is a lack of adjacent regions with suitable climate space, 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. Understanding species autecology and interactions with other species are also important to making an informed decision

There were also some differences in the balance of actions recommended by JNCC and the decision framework. For example, whilst JNCC's recommendations do not promote buffering of edge impacts, the 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 decision framework. This reflects the decision framework's closer adherence to the 'Lawton recommendations' by increasing site quality and size before addressing intervening landscapes (Lawton *et al.* 2010).

Comparing recommended actions from the decision framework across habitat types, there were more similarities than differences. In all cases, in future projected climate space, in-situ management was a high priority. However, 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 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 grassland sward, which is likely to aid adaptation of many grassland species. Future work might, therefore, repeat this analysis for a greater number of species.

There were a number of limitations encountered during the process of running species through the decision framework, which we summarise below. Firstly, there was often a lack of species data with which to answer certain questions. To deal with this we took multiple routes through tree, but this does lead to uncertainty in the most appropriate actions recommended. Further monitoring and research into species is essential to inform conservation and climate change adaptation. Secondly, 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 the UK might become either an adversely sensitive area or new climate space. Although this is an extreme example, nonetheless, we must recognise that, whilst climate space models provide 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 can they account for changes in 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 larger than the direct impacts in some cases (Smithers *et al.* 2008). Therefore, it will be essential to monitor species responses as climate change proceeds.

With regard to the decision framework, an issue was identified regarding its promotion of actions to facilitate colonisation by improving habitat connectivity even where very large distances between current and future suitable climate space would make this difficult. We dealt with this problem by introducing an additional question in the new climate space decision tree (Figure 4.3). More broadly there are a number of issues around increasing connectivity, including which species benefit most from it, whether it increases the risks posed by the spread of invasive species and its relative efficacy compared to improving site condition and thereby increasing propagule pressure to facilitate dispersal. This approach can't answer all these questions, which will in any case be case specific, but it can at least help to narrow the range of circumstances in which increasing connectivity is potentially useful.

Future work building on this current study could run a greater number of species, (e.g. ideally all NERC Act 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) across taxa. 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 species in order to identify the overall priorities for the UK and by region that emerge from deploying the decision framework.

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 that facilitates adaptive management (Mitchell *et al.* 2007) 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).

Project synthesis

This study provides the first comprehensive assessment of the likely impacts of climate change on a wide range of taxa in a particular country. In order to achieve this for over 3,000 species, a basic version of the published Thomas *et al.* (2011) framework was used (the basic framework). The results from this were broadly supported by the application of the full Thomas *et al.* framework to 400 species, although the latter classified a greater proportion of species as less likely to be impacted by climate change, as a result of incorporating information about the extent to which observed population or distributional changes are consistent with or attributed to climate change. The basic framework is therefore likely to over-attribute observed changes to potential impacts of climate change if they are consistent with future projections, but also to under-estimate the potential magnitude of climate change if observed changes as a result of non-climatic factors, are opposite to future projections. The results from the analysis of abundance (as opposed to distributional data) conducted on Annex I and migratory bird species were also qualitatively similar to those from the full Thomas framework. Thus, there was broad agreement of some of the general findings from the application of this risk assessment.

Firstly, there was evidence that northern and upland species were at greatest risk of detrimental climate change impact, which matches the results of previous assessments (Green *et al.* 2008, Thomas *et al.* 2011, Renwick *et al.* 2012). Whilst this may be intuitive for species limited by temperature, work from California suggests that for species whose populations or distributions are largely driven by precipitation may show different patterns (Tingley *et al.* 2012). Related to these spatial patterns, were some clear taxonomic differences in the apparent sensitivity of species to climate change. Thus, a large proportion of bryophytes appeared to be at risk of detrimental climate change impacts, which again, is not surprising given the high proportion of northern and upland species included in this group (Ellis 2013). Similarly, many of our northern and upland breeding birds appear to be vulnerable to climate change impacts, reflecting known impacts (e.g. Frederiksen *et al.* 2004, 2006, Pearce-Higgins 2010, Pearce-Higgins *et al.* 2010). Conversely, a large proportion of Hymenoptera, which have a very southern distribution, were classed as likely to have increased opportunity for range expansion as a result of climate change.

Although the results of this framework should be applied with care, particularly for species where there is evidence that non-climatic factors are known to have driven recent population or distributional changes, this project has usefully outlined some strong common patterns, and identified particular species and species groups likely to be most at risk from future climate change impacts. Although many of these findings support previous work, they do so for individual species in a standardised and repeatable way. In particular, for the species to which the full framework was applied, the assessment was the product of a detailed assessment incorporating additional ecological information about potential constraints on the ability of species to respond to climate change. Although these species-specific results should continue to be interpreted in the light of ecological knowledge of the species involved (particularly for those only assessed using the basic framework), this report provides as comprehensive assessment as possible of the likely vulnerability of species in England to a changing climate, and a framework for how this assessment can be updated as more information becomes available.

The second part of the report considered the potential implications of these findings for adaptation. Adaptation options for these different groups of species appear to clearly divide into two forms. Firstly, for species being adversely affected by climate change, site management may present the main opportunities to reduce the rate of potential future losses. For example, for 34 breeding bird species at risk of detrimental climate change impacts, potential management measures to be applied at individual sites could be identified for half, although for only eight species were these regarded as having demonstrable efficacy. Whilst there is considerable uncertainty about the potential for such management to be effective, there is increasing evidence that such approaches may increase the resilience of vulnerable populations to at least some degree of warming (Frederiksen *et al.* 2004, Pearce-Higgins 2011, Carroll *et al.* 2011). Even if such management may ultimately be overtaken by climate change in the long-term; adaptation options for golden plovers in the Peak District is estimated to have the potential to increase the resilience of the population to 2 ˚C of warming (Pearce-Higgins 2011), and such sites may provide dispersers for the colonisation of other more resilient sites less affected by climate change. For example, the colonisation of newly created sites by bitterns has been largely fuelled by productivity at sites which will be lost in the not too distant future from sea-level rise (Gilbert *et al.* 2010). Given the vulnerability of northern and upland breeding birds, seabirds and wintering waterbird populations to climate change, and more broadly, NERC priority species in upland habitats, it is in these environs and for these species, that the development and testing of effective management options is most required. In the absence of such interventions being possible, and if assumptions of projected climate change impacts are correct, then possible options are *ex-situ* approaches or accepting the loss of populations (Oliver *et al.* 2012). Whilst some might argue that accepting such losses is an effective use of limited conservation resources, further monitoring and research is required in these situations in order to identify and diagnose the causes of change, and to ensure that any potential adaptation management options have been fully pursued (Pearce-Higgins 2011).

Secondly, for species likely to expand their distribution, then various forms of habitat creation could be prioritised, either to provide locations for colonisation, or to increase the size of existing protected areas, depending upon the species. For about half of the bird species assessed, the potential for range expansion was regarded as potentially limited by suitable habitat. This makes the continued protection or creation of areas of suitable habitat for colonisation a key priority action that was also reflected by the application of the Oliver framework to 30 non-bird species. There is increasing evidence that the protection of natural and semi-natural habitats, for example within protected areas such as SSSIs, may actually facilitate range-expansion (Thomas *et al.* 2012, Hiley *et al.* 2013, Lawson *et al.* 2013, Johnston *et al.* 2013), making the protection and creation of such habitats a key adaptation option. The constraints on the ability of potential colonists to make use of such areas remains relatively poorly understood however.

There is a hint that the potential impacts of climate change may be more detrimental for species of conservation concern. Thus a greater proportion of NERC priority species were regarded as being at medium or high risk from climate change compared with the results for all species. An even higher proportion of Annex I and migratory bird species were found to be at risk, although this finding was based on a different analytical approach based on measures of abundance. Given the incorporation of exacerbating factors associated with small population size or additional constraints, we might expect this pattern to be even more obvious as an outcome from the full framework, emphasising the likelihood that small, rare and declining populations are more likely to be sensitive to climate change impacts than other species. This means that a key adaptation option for all species is then to reduce the severity of other threats (Hodgson *et al.* 2009, Pearce-Higgins *et al.* 2011).

Finally, a key element of uncertainty for most taxa (with the possible exception of birds and butterflies) is the lack of good monitoring and research. Given the well-recognised importance of a broad range of biodiversity for ecosystem functioning and services (Balvanera *et al.* 2006), it is clear that expanding the scope of existing monitoring and research is essential. This was a key priority that arose from the application of the Oliver framework to 30 non-avian species that was also echoed by the comments of taxonomic experts, who flagged up the limitations firstly of the underpinning distribution data for many sparsely recorded species, and the difficulties of attributing change to climatic change (Appendix 5). This poses real challenges for the effective conservation prioritisation of species to account for climate change. Certainly current species priorities should continue, but the use of the framework results to identify future species priorities should always be done in the full knowledge of the limitations of the underpinning data and knowledge, and accounting for species-specific factors. This may mean that, in some cases, the results of this assessment should be altered as new information comes to light.

To conclude, this process has identified a list of species that we regard as likely to be at high risk from climate change, and others for which climate change may produce opportunities. This information can be used to identify the adaptive conservation responses for these species and, particularly at the species level, to consider the potential constraints on species which may exacerbate any climate change losses, or limit the potential for climate-related expansion. Negative impacts could be addressed through site management, whilst habitat creation may promote the expansion of other species, although much work is required to test and validate these potential approaches. The information in this report, alongside other sources, may therefore be used by species specialists to help guide and target future conservation action to the most vulnerable species, and to promote the recovery of those which are currently vulnerable but may face opportunities from climate change. Finally, we would not suggest that the results of this work be used to advocate the cessation of conservation action on particular species which the framework suggests are at high risk of climate change. For these species, the potential for *in situ* management to counter such pressures should be explored, alongside effective monitoring, in order to diagnose potential climate change impacts and identify whether such management is indeed working or not.

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Appendix 1: Occupancy models to account for observer effort

There is an essential asymmetry in all presence absence data: whilst presence is certain (ignoring identification errors), absence is not (Royle *et al.* 2005). Simply because no observations of the species of interest have been made from a particular cell does not ensure that the species really is absent, as the species may be present at low density, but the site insufficiently sampled to detect the species. When sampling effort is variable across space or time, this presents a particular problem for modelling distributions and analysing change. To address this problem a family of statistical models have been developed called 'Occupancy Models' that attempt to assess independently the probability of detection given that a species is present, from the underlying probability of presence. Full details of this class of models can be found in recent textbooks (MacKenzie *et al.* 2005), but in essence they are hierarchical models with two layers: one layer a traditional niche model, relating probability of occurrence to habitat / climate variables, and a second layer relating observed patterns of presence / absence to the observation process to produce probabilities of presence. As originally conceived, occupancy models require multiple observations from the same cell to identify the probabilities of observation separately to the probability of occupancy. As our data lack repeat visits, we used an occupancy model that took observer effort (estimated as the proportion of species expected to be present in a square that had actually be observed, using the model of Hill 2011) and estimated the probability of observation given presence as a decelerating function of observer effort. More precisely, we fitted a single parameter exponential function, with intercept of zero and asymptote of one, where the single parameter can be interpreted as a species-specific observability score: cryptic species require much higher effort to be confident of discovering, whilst large, obvious and abundant species are quickly found.

As our occupancy models are an advance on familiar species distribution models, we assessed both the need to use more complex models and any statistical artefacts that may be introduced into the modelling process. In preliminary analyses of the BRC datasets it rapidly became apparent that spatial variation in observer effort caused enormous problems for modelling even common species with many records in the database. Consider the example of the Silver Birch *Betula pendula*. This species is widespread across the UK and easily identified, so an appropriate model should show nearly ubiquitous high probabilities of presence. We modelled the observed distribution (Figure A1.1a) using the basic, spatially explicit niche model (Figure A1.1b), and using occupancy models based on two alternative estimates of plant-specific observer effort (calculated using the methods of Hill 2011): the proportion of benchmark species recorded in each cell (Figure A1.1c) and the proportion of all expected species recorded in each cell (Figure A1.1d). It is immediately obvious that although observations are (correctly) widespread across the UK, the frequency of records within the BRC database is greater in some vice-counties than others: Devon, Cornwall, Northumberland, Lancashire and Essex are all extremely well covered, whilst records in other regions are patchier. Although this could reflect real variation in distribution, it seems more likely that the many gaps represent lack of recorders, rather than true absence of the species (especially as records since 1990, with wider geographical coverage confirm the presence almost everywhere). It is also immediately clear that the naive distribution model is virtually useless at describing the true range, being heavily biased towards well recorded regions. Both occupancy models are much better (suggesting that any accounting for variation in observer effort is much better than none at all), and after considering results for a variety of species we adopted the estimate of observer effort based on the proportion of all expected species that have been recorded in each cell as our chosen measure of observer effort (Figure A1.1d).

Having established the need to use occupancy models for the BRC data, we remained concerned that our preferred occupancy model may somehow introduce bias into the risk assessment analysis. To explore the effect of using the occupancy model, rather than simpler options, we used the well recorded bird dataset to assess the impacts of using the more complex model on a dataset where the need for the occupancy modelling has been considered minimal. Consequently, we fitted two models to each of the bird datasets, one using no occupancy model, one using an occupancy model based on a bird-specific observer effort index using the proportion of all expected species recorded in each cell. Parameter estimates were used in the usual way to estimate proportional range change for both methods and the results compared (Figure A1.2).

From these results two important conclusions can be drawn: (1) when observation effort is generally good (as for birds) there is a very strong correlation between estimated changes from naive models and those from occupancy models. (2) The effect of using an observation model is to (marginally) decrease the degree of change expected when compared to the simpler model. Both these results are intuitively reasonable: the former contrasts with the example of the Silver Birch where observer effort varies substantially in geography and the occupancy model is very important, confirming the method makes adjustments to the expected distribution only when observer effort is poor. As the only impact of an occupancy model is to increase the estimates of probability of presence in some squares with observed absence (thereby increasing the estimated range), the second result is also sensible: with a larger estimated range, there is a smaller area available to expand into but a larger area for contractions to occur within.

Overall, these results strongly support the use of occupancy models whenever observation effort can be estimated, and suggest that any potential biases introduced by using the more complicated model are far smaller than the problems caused by not accounting for observer effort.

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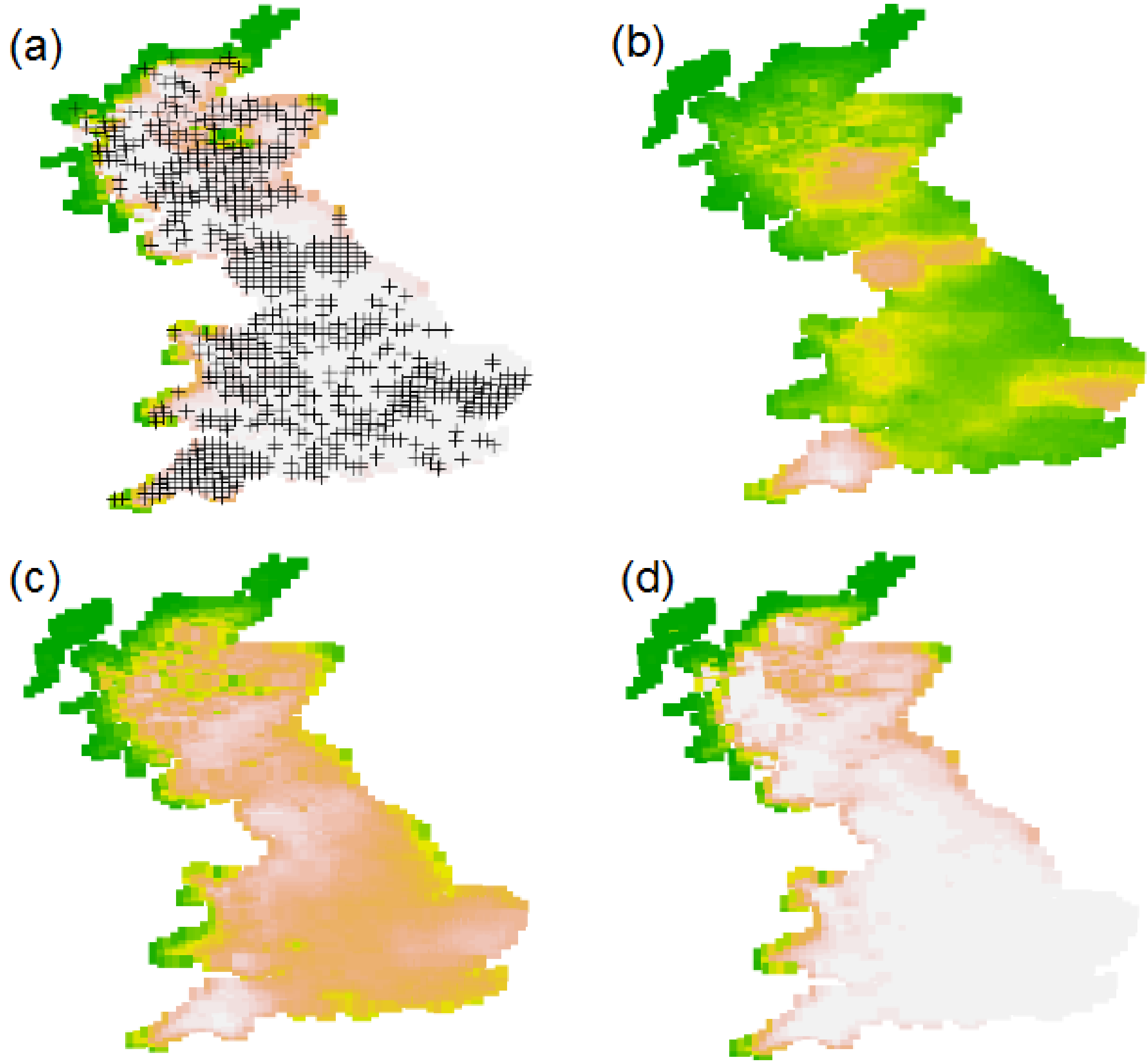

Figure A1.1 Occupancy models for *Betula pendula*. (a) Presence records in the BRC database during the observation period (crosses). (b) Modelled distribution (white = high probability, green = low) using a spatially explicit distribution model with no occupancy model. (c) Modelled distribution from a spatially explicit occupancy model using proportion of benchmark species. (d) Modelled distribution from a spatially explicit occupancy model using proportion of all expected species

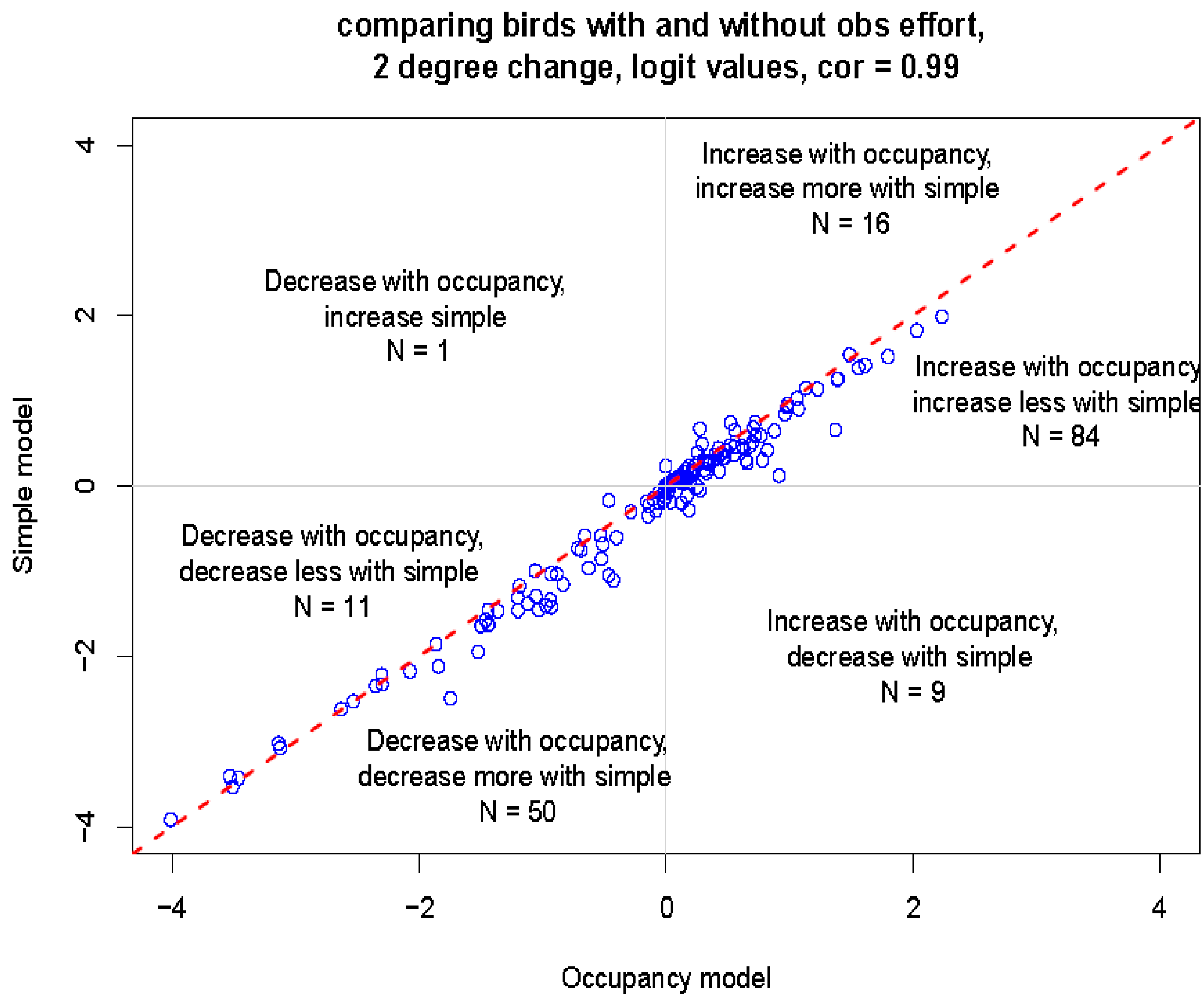

Figure A1.2 The relationship between estimated range changes under a 2 degree global change warming scenario for simple spatially explicit models and spatially explicit occupancy models for UK birds (where observer effort is not expected to cause significant problems). The correlation between the two sets of results is 0.99

Appendix 2: Details of the species distribution data

Species distribution data for Great Britain were acquired from the Biological Records Centre and British Trust for Ornithology at a standard 10 km resolution. Data were available for the following groups: ants, spiders, bees, birds, bryophytes, butterflies, carabid beetles, centipedes and millipedes, Cerambycid beetles, Coccinellids, craneflies, hoverflies, moths, dragonflies and damselflies, crickets and grasshoppers, plants, soldier beetles and wasps (Table 1). Cells for which climate data were not available were excluded from analyses. Cells on small islands, isolated from the UK mainland, were also excluded to aid model convergence. This gave 2,561 10 km × 10 km cells for inclusion in analyses of Biological Records Centre data (all groups except birds), and 2,670 cells for analysis of bird data (which included the Hebrides and Shetland islands as observer effort remained good for birds in these areas). For all groups other than birds and plants, distribution data were taken only from the period 1970-89; bird data were taken directly from the Second Breeding Bird Atlas, so referred to the period 1988-91; plant data were taken from the period 1970-86, thus covering the period of the BSBI atlas (Preston *et al.* 2002).

Species distribution data for Europe were acquired from the European Bird Census Council and the Atlas Florae Europaeae. For birds, distributions at the European and British scales were matched by matching species names in the two datasets. For plants, however, taxonomy sometimes differed between the two datasets, so distributions were matched in two stages. First, species with identical names in both datasets were identified. Second, if the genus was present in the AFE data but the species name was unmatched, species were manually matched by searching for synonyms or subspecies in the European dataset. For any British species with multiple matches (e.g. when multiple subspecies were listed in the European data but only one identified in UK), the European data were combined into a single distribution. Within the European data, presences were defined only by records of native occurrences. For all European datasets, cells from Eastern Europe were not included to avoid problems of low observer effort; the maximum longitude was 29.99°. Iceland and the Faroe Islands were further excluded from model fitting to aid model convergence. This gave 2,644 50 km × 50 km cells for inclusion in analyses.

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Appendix 3: Comparison of model results from Europe/UK data and UK only data

An important decision that needs to be made when building a species distribution model is the spatial domain that will be used. Too small and the likelihood of adequately quantifying all climatic limits of the niche are limited, too large and the model risks being altered by so-called 'naughty naughts' (Austin & Meyers 1996). An additional problem arises when attempting to forecast distributions under climate change where future climates may be very different from any currently existing climates (Williams & Jackson 2007). This can be a particular problem when forecasting distributions within a restricted domain, such as the UK, so it is important for us to assess the impact of our domain choice on the distribution of novel climates.

There is no standard calculation available to estimate the presence of non-analogue climates. In a minimal sense, it is simply places where future temperatures (or rainfall, or any other climate variable) are expected to fall outside the current range of temperatures. However, climate variables covary such that a multidimensional measure may be more appropriate: it is perfectly possible to identify locations where the future combination of temperature and rainfall may fall outside the current set of temperature and rainfall combinations, but neither individual parameter falls outside the current range of variation. A more restricted definition (but arguably not overly strict) would therefore be to define non-analogue climates as any combination of future temperature and rainfall that falls outside of the minimum convex polygon describing all current temperature and rainfall combinations. Our models used four bioclimatic variables (a relatively minimal set), so we used a four-dimensional convex hull to define the current environment space - a simple extension of the two-dimensional minimum convex polygon (note that as dimensionality increases, the volume of a hypersphere necessarily declines). Using UK only datasets, we identified all the locations that have future climates that fall outwith the current four-dimensional convex hull describing current climate space (Figure A3.1a and A3.1b). Even under the low (2 degree global change scenario) *all* the future English climate space is novel, suggesting that all models from UK only datasets should be treated as uncertain. Note that the area of novel climate space within any given geographical domain is totally dependent on the volume of the hypersphere within which current climate is contained. As the volume of a hypersphere declines with increased dimensionality, the (essentially arbitrary) choice of how many climate variables to include in a definition of climate space has a huge impact on the estimated area of novel climate space.

An obvious solution to this problem is to extend the spatial domain to a larger area where climate analogues for the focal region may be present (whilst still restricting the domain sufficiently to minimise the 'naughty noughts' issue). Earlier British studies (e.g. the MONARCH project; Harrison *et al.* 2001) attempted to solve this problem by first modelling European distributions, and then using the output of European distributions as an additional input into finer-scale UK analyses. This approach is sound in theory, but the particular implementation within the MONARCH project rendered the additional step uninformative. Here, for plant species with distributions published in the Atlas Flora Europaeae (a subset of only 354 species) and for bird species published within the European Bird Atlas we used a different approach, treating the information gained from a European scale analysis as prior information that can be refined (or not) using the UK only dataset. Our Bayesian analysis approach makes propagation of information from one, large-scale, analysis to another, smaller-scale, dataset simple through the use of Bayesian priors, meaning that niche limits that may be found only in warmer parts of Europe (such as southern France) can be used to forecast future distributions in the UK. Consequently, we repeated our analysis of novel climate space, this time using the minimum convex hull for current European climate space. As expected, the impact of novel climates within the UK for these models is much less (Figure A3.1c, d), with 90% of future climates having a current analogue elsewhere in Europe.

This gives us confidence that birds and those plants with published European distribution data are likely to be well modelled. Consequently, we used this subset of species to compare UK forecast changes when modelled using European and UK data, to those for the same species modelled using only the UK data (i.e. emulating the modelling procedure for those species where European data was not available). These results are presented in Figure A3.2, from which the following can be observed:

- There is a significant, positive correlation between the two sets of results (r^2 = 0.477).
- There is no significant difference in the slope of the relationship between the EU/GB results and GB only results between birds or plants (F1,528 = 0.052, *P* = 0.820).
- The UK only projections are generally more pessimistic than the European / UK two-stage analysis (58% of species [57% of birds, 58% of plants] are forecast to increase in the EU/UK analysis vs. 46% from the GB only analysis).
- In 26% of cases (18% of birds, 31% of plants) one model predicted increases, whilst another predicted decreases (differences between birds and plants are likely due to the noisier plant data).
- In 7% (2% of birds, 10% of plants) of species the more reliable model (EU/UK) predicted a decline in range, whilst a UK only model would have suggested the species as not at risk.
- UK only results tended to be more extreme than EU/UK results in both expansion and contractions (i.e. species that both analyses predicted to expand were generally forecast to expand more using UK only models and species which both methods predicted to contract species were generally forecast to contract more).

Overall, these results can be summarised as suggesting that for the majority of species, although novel climates across most of UK lead to considerable uncertainty, we remain fairly confident that our projections are informative. However, we do draw attention to the tendency of

UK only models to generate more extreme results and consequently urge caution when interpreting the overall level of risk from climate change.

Austin, M., & Meyers, J. (1996). Current approaches to modelling the environmental niche of eucalypts: implication for management of forest biodiversity. *Forest Ecology and Management*, *85*(1), 95-106.

Harrison, P. A., Berry, P. M., & Dawson, T. P. (2001). *Climate Change and Nature Conservation in Britain and Ireland: Modelling natural resource responses to climate change (the MONARCH project)* (P. A. Harrison, P. M. Berry, & T. P. Dawson). UK Climate Impacts Programme.

Williams, J. W., & Jackson, S. T. (2007). Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment*, *5*(9), 475-482.

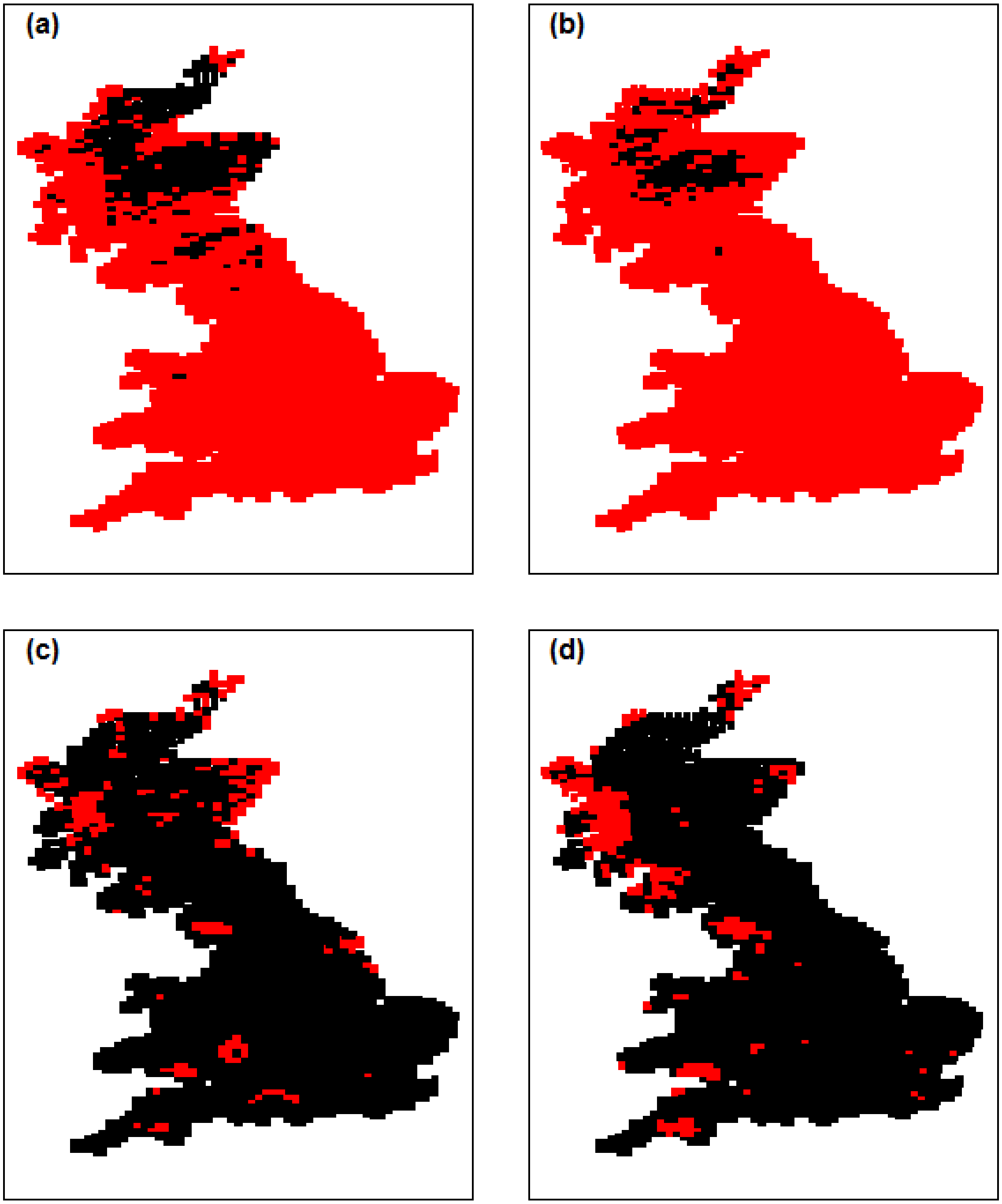

Figure A3.1 Non-analogue climates from (top row) British only and (bottom row) European current climates under (first column) 2 degree global warming scenario and (second column) 4 degree global warming scenario defined using the current British climate space. Red cells indicate novel climates (a) Britain only, 2 degree scenario (85% novel), (b) Britain only, 4 degree scenario (94% novel), (c) Europe, 2 degree scenario (9% novel), (d) Europe, 4 degree scenario (10% novel)

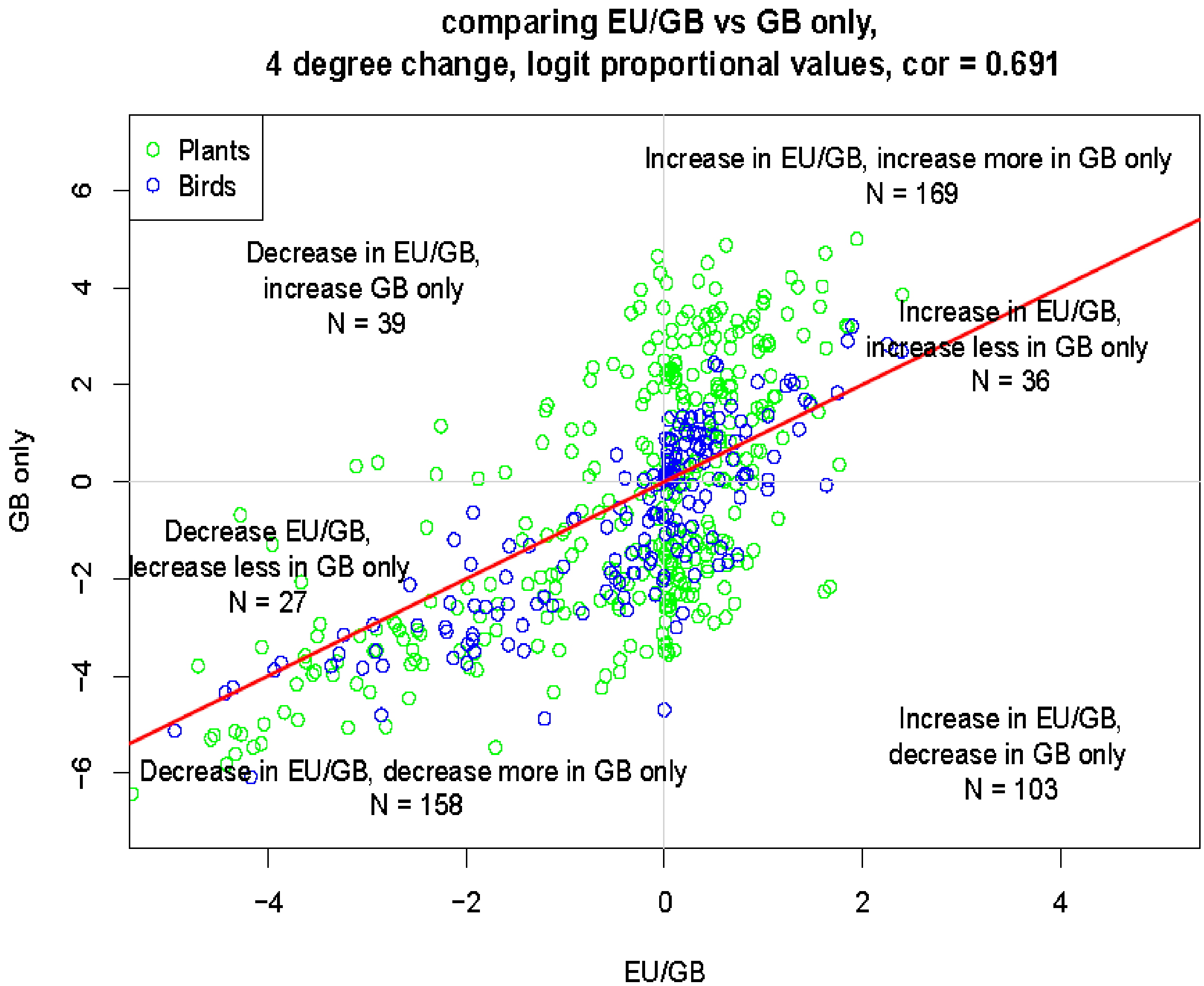

Figure A3.2 Correlation between modelled results for bird and plant species modelled both using UK only data, and using the European / UK two-stage analysis.

Appendix 4: Comparison of bioclimate projections for 2 and 4 degree scenarios

There is considerable uncertainty over the magnitude of future climate change, primarily due to uncertainties surrounding the human response to the threat it poses. Even the most optimistic scenarios for limiting future climate change suggest that a 2°C global rise over baseline by 2080 is essentially inevitable. Current estimates suggest 4°C may be a more realistic mid-level scenario. It is widely perceived that limiting change to 2°C will avoid most dangerous climate change. Consequently, we sought to quantify the difference in threat associated with climate change consistent with global temperature change of both 2 and 4°C.

It is important to note that a global change of 2°C does not imply that local temperatures in all locations will increase by 2°C, and in general northern, terrestrial regions are expected to experience greater change than many other areas. Using the 11 UKCIP09 spatially coherent projections for the two scenarios that generate 2 and 4°C warming globally results in mean forecast changes in mean annual temperature of 3.6°C (range 2.8 - 4.4°C) and 4.1°C (range 3.6 - 5.5°C) respectively. Similar results are found for total annual precipitation, with mean increases of 37.8mm (range -16.8 - 112mm) and 57.9mm (range -14.1 - 159.3mm) for 2 and 4°C warming globally. From this is it clear that there may be relatively little difference between the two climate change scenarios for the UK: the distinction between 2°C as 'safe' and 4°C as 'dangerous' climate change is a global distinction not of major consequence for the likely climate within UK. Note further, that changes in different seasons may be greater than the overall mean temperature change and that we converted raw climate variables into biologically meaningful variables that may show more or less extreme changes than the overall mean annual temperature.

The simplest comparison of the predicted changes in species distributions for 2 and 4°C future scenarios is to plot the projected changes against one another (Figure A4.1). From this figure it is immediately obvious that the results are highly, positively correlated ($r^2 > 0.99$). It is further clear that exactly as expected, changes forecast under the 4°C scenario are generally more extreme than those forecast under the 2 degree scenario: increasing species are forecast to increase more, decreasing species are forecast to decrease more. There is no difference in the slope of the line for birds or plants ($F_{1,528} = 0.914$, $p = 0.340$). However, the difference between changes between 2 and 4°C are small, relative to the changes that occur. For example, a species increasing to fill 60% of the currently unoccupied range at 2°C may increase to fill 63% at 4°C. Importantly, there is relatively little evidence that many species (c. 1%, close to the expected error) may experience opportunity from a 2°C change, but lose suitable climate space under a 4°C global warming scenario. It is therefore clear that within the UK there is relatively difference in the biological impact of 2°C global warming and 4°C global warming.

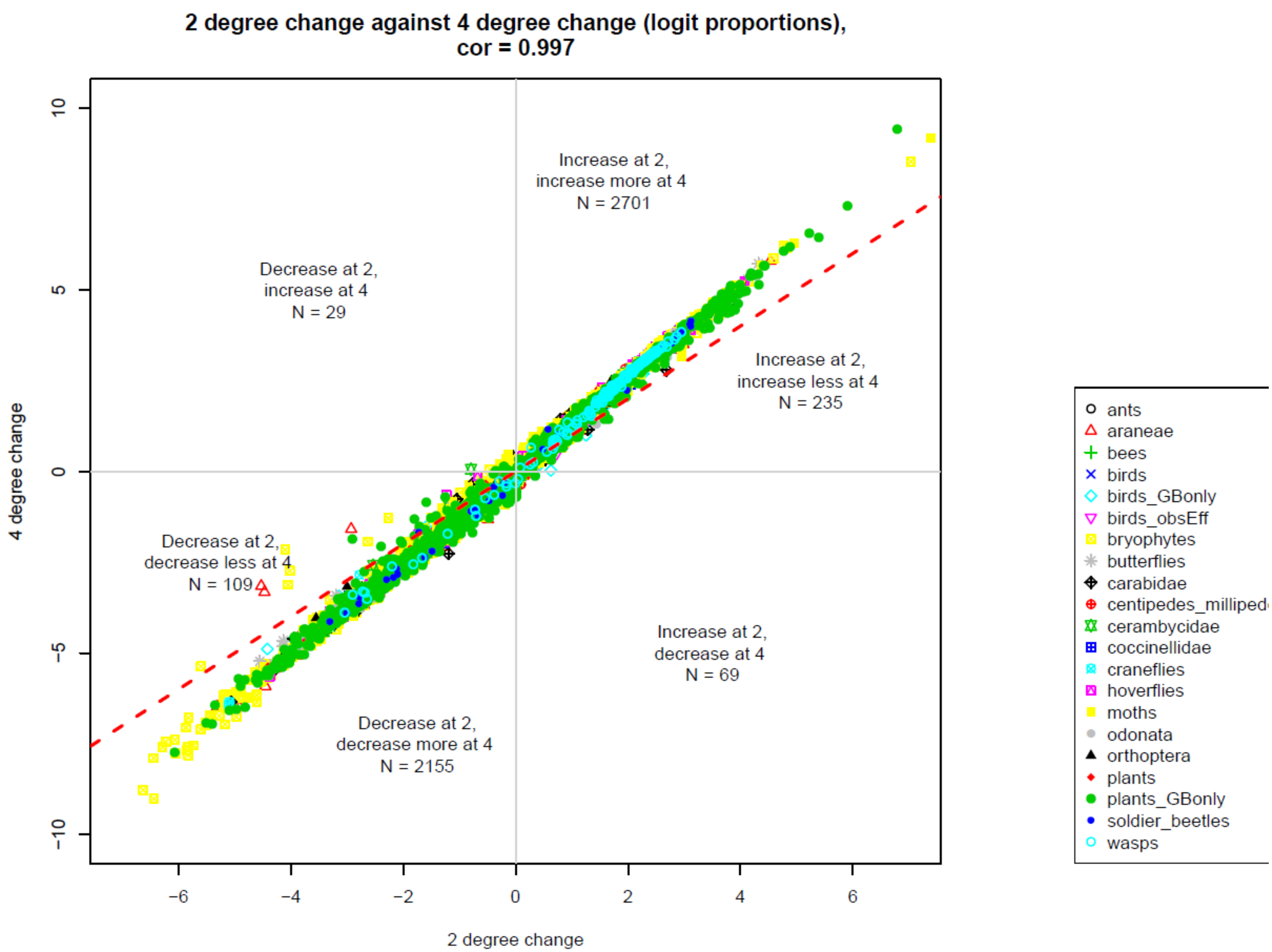

Figure A4.1 Projected distribution changes under 2 and 4°C global warming scenarios. Raw changes in probabilities have been converted to changes proportional to the available space for change: increases are expressed as a logit proportion of currently unoccupied space, decreases as a proportion of currently occupied space

Appendix 5: Comments on the process provided by scheme recorders

Five species experts provided input on climate change impacts as part of the risk assessment (Chapter 1). As part of the process a number of concerns were raised which we have summarised here.

Limited species coverage

The aim of the risk assessment was to explore the potential of providing a climate change risk assessment across a broad range of species groups (Table 1.1). However, some experts felt that this small random subset was not necessarily representative

"….*on a fairly small random selection,* ***risks a serious distortion in the overall applicability****. (7 of your species fall into this category, with a random sample including 3 from the same genus (Sphecodes), which has 16 non-Channel Island species in the list. Compare this with Andrena, where just 2 species are represented from 50ish species and Lasioglossum with 3 species from 30ish*". (Mike Edwards, Bees, Ants and Wasps)

Recording coverage

Many experts were concerned about the analysis of data where recorder effort varied markedly across regions and over time.

"*It is important to bear in mind that for many less well recorded taxa the datasets are relatively small for each year. ......Examples include Anasimyia lunulata, which was relatively well-recorded in the late 1980s because of the Welsh Peatland Invertebrate Survey, but has not really been looked for since. Similarly, more effort in Scotland would skew Eristalis rupium, which can be abundant in some places, but Scotland is very poorly recorded if compared to southern England*" (Roger Morris, Hoverfly Recording Scheme)

"*Even then the impact of one recorder starting to document the fauna of an area outside the known range of a species can easily give a false impression of expansion. This happened in Perth and Aberdeen in the 1980s. Equally if a previously active recorder stops work in an area it can create a false impression of decline. This occurred in Bedfordshire in the 1980s. I know this is a problem with all groups but has been a particular issue with the myriapod recording schemes which have relied on a very small core of active recorders generating the vast majority of the data".* (Paul Lee, Spiders, Millipedes and Centipedes)

"It is my feeling that this list builds in inherent weaknesses because the data for each year are pretty sparse in most instances and can be heavily skewed by activity in a particular area.." (Roger Morris, Hoverfly Recording Scheme)

"There has been targeted effort on many (not quite all) of these species, so that could be the reason for the suggested increase, but then there is likely to have been an element of under-recording prior to this". Mark Parsons (Moths)

"Some species, notably in the dryinids and bethylids have strongly skewed distributions relating to collector effects". (Mike Edwards, Bees, Ants and Wasps)

However, analyses detailed in this report were designed to take into account this spatio-temporal variation in recorder effort (see Chapter 1 methods and Appendix 1).

Taxonomic issues

For a few species there were taxonomic issues that were not fully resolved (i.e. whether species records in the database actually pertain to two separate subspecies). In the future, experts suggested filtering out cryptic species for which there is likely to be considerable taxonomic confusion because they are difficult to identify.

"Some of the trend data for these species need to be treated with caution because of recent splits – for example, Eupeodes bucculatus has only recently been separated from E. goeldlini and we really don't have a clue how the data really lie." (Roger Morris, Hoverfly Recording Scheme)

"It includes several species that are extremely difficult to identify (Cheilosia nigripes, Eupeodes nielseni, Eupeodes bucculatus) and contains just two species (Spaherophoria scripta and Xylota segnis) that might be expected to be reported by the 'average' recorder. The dataset is therefore relatively skewed towards species whose distribution is less well-known and whose biology is arguably more difficult to judge." (Roger Morris, Hoverfly Recording Scheme)

Difficulties in attributing climate change impacts

During the parameterisation of the risk assessment it became clear that for many scarce species little is known about their autecology, and there was a clear need for more research.

"*Developing a policy framework for a response becomes even more difficult because many species in less well-known taxonomic groups have very specific needs; often unknown to us."* (Roger Morris, Hoverfly Recording Scheme)

Appendix 6: Information and criteria used in running species through the full Thomas framework

Stage	Data sources and criteria used
I.A.impact	For bird species the decadal decline within current range was calculated from Atlas data between 1990-2010. For all other taxa, a mixed effects model on BRC data controlling for recorder effort using trend was used.
I.A.confidence	All bird species trends were assigned with good confidence. For other taxa, confidence was based on the C. I. from mixed model: if upper 80% C.I. overlaps the next impact category then confidence is poor, otherwise good.
I.B.impact	If both observed trend (I.A.) and projected trend (II.A.) are negative then linkage="Yes". Supplemented with literature review to assess additional linkages with climate
I.B.confidence	Poor if just assessed by comparison of observed (I.A.) and projected (II.A.) trends. Good if robust evidence identified by literature review.
I.C.i.impact	Is current extent <20 000km^2? * Additionally for bird species only: is British population < 10 000 individuals?
I.C.i.confidence	For bird species generally good. For other taxa: poor if just assessed by using current extent data. Good if robust evidence identified by literature review or supported by expert opinion.
IC.ii.impact	Expert knowledge or evidence from literature review supporting at least one of the factors.
I.Cii.confidence	Good if robust evidence from peer-review literature. Poor if based on expert knowledge alone. For birds, due to generally good understanding of the ecology of these species, experts were asked to assign the confidence level where impact was based on unpublished information.
I.D. summary	Combine results from stages A to C to provide an overall assessment of impact and associated confidence level.
II.A.impact	Bioclimate model projected change in occupancy within current range
II.A.confidence	a) Is bioclimate confidence intervals below a threshold value (see main text)? b) Is direction of projected trends (II.A.) in same direction as observed trend (I.A.)? For bird species: Yes to (a) & (b) = good, yes to (a) only =medium, no to (a) =poor. For other taxa: Yes to (a) & (b) = good, yes to (a) or (b) only =medium, no to (a) & (b) =poor.
II.B.	Not applicable
II.C.i.impact	As I.C.i
II.Ci.confidence	As I.C.i
II.C.ii.impact	As I.C.ii
II.Cii.confidence	As I.C.ii
II.D. summary	Combine results from stages A to C to provide an overall assessment of projected impact and associated confidence level.

Stage	Data sources and criteria used
III.A.impact	For bird species: decadal increase outside previous range was calculated from Atlas data between 1990-2010. Other taxa: mixed model of BRC data of observed increases beyond species' recent historical range** controlling for recorder effort
III.A.confidence	All bird species trends were assigned with good confidence. For other taxa: the model output was compared across 3 different levels of recorder effort - if the level of recorder effort changes the impact category then confidence is poor, otherwise assigned as good.
III.B.impact	If both observed trend (III.A.) and projected trend (IV.A.) are positive then linkage="Yes". Supplemented with literature review to assess additional linkages with climate.
III.B.confidence	Poor if just assessed by comparing observed (III.A.) and projected trends (IV.A.). Good if robust evidence identified in literature review.
III.C.	Not applicable
III.D. summary	Combine results from stages A & B to provide an overall assessment of impact and associated confidence level.
IV.A.impact	Bioclimate model projected change in occupancy outside the current range
IV.A.confidence	As II.A.
IV.B.	Not applicable
IV.C.i. impact	Expert knowledge or evidence from literature review supporting at least one of the factors.
IV.C.i.confidence	Good if robust evidence from peer-review literature. Poor if based on expert knowledge alone. For birds, due to generally good understanding of the ecology of these species, experts were asked to assign the confidence level where impact was based on unpublished information.
IV.C.ii. impact	As IV.C.i.
IV.C.ii.confidence	As IV.C.i.
IV.C.iii. impact	As IV.C.i.
IV.C.iii.confidence	As IV.C.i.
IV.D. summary	Combine results from stages A to C to provide an overall assessment of projected impact and associated confidence level.
V. Overall Summary	Combine information from Stages I to IV to provide an overall summary of the risks and opportunities from climate change.

Please note we occasionally changed confidence levels in Stage A (usually 1.A.) if experts highlighted concerns regarding distribution data, e.g. significant changes in recorder effort, recent taxonomic splits, issues regarding taxonomic identification etc.

*Current extent is calculated by bioclimate model: probability of a cell being occupied multiplied by the area of a cell = current extent (possible area occupied)

**Number of newly occupied cells outside the current range as a percentage of cells inside current range