Biodiversity under climate change: biogeography, prospects and conservation opportunities

Christopher John Wheatley

PhD

University of York

Biology

August 2018

Abstract

Global climate change is one of the largest threats faced by biodiversity globally, with a wide range of impacts already observed and greater impacts projected to occur by the end of this century. Early identification of which species are most threatened by climate change is crucial to ensuring conservation action can be taken to prevent species losses. In this thesis I analyse the performance of a wide range of methodologies used to assess the risk to individual species from climate change, finding overall poor agreement between the different methods and validation using historic data sources demonstrated few were good predictors of climate change risk. A comprehensive trend-based climate change vulnerability assessment for European birds and butterflies was carried out, using the best performing methodology identified in this thesis. Differing patterns of climate change risk were identified for the two taxonomic groups, with a mix of risk and opportunities for birds but an overall substantially higher level of risk for butterflies. A large proportion of the species categorised as high climate risk are not of conservation concern currently and may be important targets for conservation intervention in the near future. Finally, a spatial prioritisation analysis for Europe identified where geographically the most important areas for conservation are located, and how the distribution of highest priority areas may change in the future. An examination of how the spatial scale at which conservation prioritisation is performed at can influence the effectiveness of the process found the currently used national scale approach within Europe is significantly less effective than either a full continental scale or a rescaled continental approach. Comparisons of these spatial prioritisations with the European protected area network show that under climate change existing sites are likely to become increasingly important in preventing the loss of species across the continent.

Contents

List of Tables

List of Figures

Acknowledgements

I am incredibly grateful to both of my supervisors at the University of York, Prof Chris Thomas and Dr Colin Beale for their constant guidance and support throughout the duration of my PhD. I could not have asked for a better pair of supervisors; I have learnt an immense amount from each of them and they have made completing the PhD a rewarding and enjoyable process.

I was also incredibly lucky to receive the additional support of two CASE supervisors as part of my project, Dr Richard Bradbury from the RSPB and Dr James Pearce-Higgins from the BTO. Both external supervisors were heavily involved in all aspects of my project from the beginning and their input has been invaluable throughout. I am also very grateful for the many opportunities to be involved with a variety of events at both partner institutions, particularly my 3 month placement with the RSPB.

Within the Biology department at York, Prof Jane Hill and Dr Elva Robinson consistently provided valuable insight, comments and discussion on my project in their role as Training Advisory Panel members, and I am thankful for them making our regular meetings positive experiences. The members of the Whole Organism Ecology lab group consistently provided useful advice and feedback; in particular Dr Rob Critchlow and Dr Phil Platts consistently provided valuable assistance with analysis and general programming issues.

I am very grateful for PhD CASE studentship funding from the Natural Environment Research Council and the Royal Society for the Protection of Birds, without this the project would not have been possible.

The support of my family and friends has been hugely important over the course of my PhD. My Mom has always encouraged and supported my academic efforts, and without her I would not be on the PhD path. My sister Alison showed me it was possible and made sure I didn’t have to be the first in the family to go through the PhD process.

My in-laws David, Dorinda, Jade and James have all been supportive of my science career and have listened patiently to my many attempts at explaining what I do. Of course a big thank you to my nephew Max for always being excited about birds.

Many friends have been forced to hear about the ups and downs of the PhD process, but in particular Jane, Paul, Dan and Kirstie all received more than their share of complaints but were always willing to listen and offer advice or encouragement.

Finally, my wife Megan who has had to suffer with more than anyone else over the last four years, but has never failed to be supportive and positive at any time. I doubt I would have made it to the end of without her, and for that I am eternally grateful.

Declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

This thesis involved collaboration with Chris Thomas (CDT), Colin Beale (CMB), Richard Bradbury (RBB), James Pearce-Higgins (JP-H) and Rob Critchlow (RC).

Chapter 2

This chapter has been published as:

Wheatley CJ, Beale CM, Bradbury RB, Pearce-Higgins JW, Critchlow R, Thomas CD. (2017) Climate change vulnerability for species - Assessing the assessments. Global Change Biology, **23**, 3704–3715.

This chapter is reproduced in full in this thesis, with minor formatting alterations. All authors conceived and designed the study; CJW, CMB and CDT collected data; CJW and CMB analysed the data; all authors interpreted the results; CJW produced the original draft and all authors contributed to revisions.

Chapter 1 General Introduction

1.1 Global Climate Change

Global climate change is now a widely accepted phenomenon, with the Intergovernmental Panel on Climate Change (IPCC) stating that “warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level” and that this current warming is “very likely due to the observed increase in anthropogenic greenhouse gas concentrations”, including carbon dioxide, methane and nitrous oxide from human activities (IPCC 2007). Since the 1950s, atmospheric and ocean temperatures have increased, snow and ice cover has declined, sea level has risen, and greenhouse gas emissions have increased, with the magnitude of some of the changes unprecedented over decades to millennia (IPCC 2014).

In this introduction I will consider the evidence that we are currently experienced rapid, human induced climate change and examine what impacts this will have on a wide range of species. I will discuss the ongoing biodiversity crisis we are experiencing across the globe, and consider how climate change is likely to exacerbate this problem in the future. I will examine what conservation management action is already being undertaken to prevent species losses, what more needs to be done to ensure the impacts of climate change on species extinction risk are adequately considered when implementing conservation management and how this thesis will address some of these issues.

The global surface temperature has warmed by ≈0.85°C since 1880 (IPCC 2013) and in the Northern hemisphere the period between 1988-2017 is the warmest 30 year period of the last 1400 years. Future climate projections indicate that this trend is set to continue and potentially worsen depending on the global response to lowering greenhouse gas emissions. Under a low emissions scenario a global temperature increase of between 1.1 - 2.9°C is projected by the end of the century, which rise to an increase of between 2.4 - 6.4°C using a high emissions scenario (IPCC 2007). In either case the rate of warming would be greater than has been recorded over the past century, with potentially wide reaching biological and ecological consequences.

In 2015 the ‘Paris Agreement’ was adopted by the United Nations Framework Convention on Climate Change, with the aim to “limit the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels” (UNFCC 2015). These are ambitious goals, although there is evidence that limiting temperature increase to even 2°C of warming will be difficult and require a substantial increase in mitigation efforts in the short term (Rogelj et al. 2016; Peters et al. 2017).

Recent climate change has already been demonstrated to have a wide range of effects on biodiversity globally, across a range of biomes and from species to ecosystem scale (Walther et al. 2002). Changes in biodiversity in response to climate change include changes in distribution and /or abundance (Hickling et al. 2006; Johnston et al. 2013), phenology (Parmesan 2006; Sherry et al. 2007) and community structure (Wilson et al. 2007b). All of these responses have been seen across a wide variety of taxonomic groups and geographic scales, demonstrating the effects of climate change will impact biodiversity globally.

One of the major changes resulting from climate change is the response of species shifting distributions to higher latitudes or elevations (Walther et al. 2002; Parmesan & Yohe 2003; Root et al. 2003; Chen et al. 2011). Poleward shifts under climate change have been reported for a range of taxonomic groups (Hickling et al. 2006; Mason et al. 2015) and although the rate of change is variable (Angert et al. 2011; Mair et al. 2014) the overall pattern is consistent, indicating there will be continued changes to communities and ecosystems in the future.

The ability of species to track changes in climate is a major issue, if species respond slowly and lag behind climate change they may be at an increased risk of extinction even if there is suitable climate space available for them to shift their distribution into. There is evidence from a range of studies to suggest that some species are already lagging behind climate change (Foden et al. 2007; Devictor et al. 2008; Bertrand et al. 2011; La Sorte & Jetz 2012), so identifying and mitigating the impacts of climate change on species at an early stage is crucial to reducing extinction risk.

Changes to phenology, or the activity period of species, are the most commonly reported biological change driven by climate (Parmesan 2006). Earlier flowering and fruiting dates in plants (Menzel et al. 2006), longer summer growing seasons (Menzel & Fabian 1999), earlier egg laying (Crick et al. 1997) and later arrival of migrants in birds (Both et al. 2006, 2009), earlier emergence of butterflies (Roy & Sparks 2000; Forister & Shapiro 2003) and advanced breeding dates in frogs (Gibbs & Breisch 2001) are just some of the many reported instances of climate change impacting on the timing of events. While some of these changes may prove beneficial to species, particularly extended growing and breeding seasons, changes in activity period have the potential to disrupt the coordination of event timing between species, resulting in dependent interactions becoming asynchronous. There is evidence that these mismatches in event timing can have detrimental impacts on species, for instance host plant availability (Inouye et al. 2000), parasitoids and their invertebrate hosts (Hance et al. 2007), predator/prey cycles (Visser & Both 2005; Gilg et al. 2009) and plants/pollinators (Memmott et al. 2007; Hegland et al. 2009).

Even for species that are not to suffer the direct effects of climate change may still suffer from indirect effects, such as increased competition from invasive species or increased exposure to disease. Climate change may make local conditions more favourable for invasive species, as seen with thermophilous garden plants colonizing surrounding countryside, which would create competition with native species for resources (Walther et al. 2002). Disease is also expected to have an increased impact on the survival of species under climate change, with warmer winter conditions increasing the survival of overwintering pathogens, leading to increased frequency of outbreaks and severity of disease (Harvell et al. 2002). Vector-borne diseases have expanded their ranges under climate change (Gratz 1999), potentially exposing communities to novel diseases they have not previously experienced. With disease already listed as a contributing factor for ~8% of critically endangered species, with continued climate change it could become an even more serious threat leading to species extinctions (Pounds et al. 2006; Smith et al. 2006).

1.2 Global Biodiversity Loss

The process of extinction occurs commonly in the natural world, with an estimated 99% of the species that have ever existed on earth have gone extinct (McKinney 1997). Normally the process of extinction is balanced by speciation, although during five time periods in the Earth's history more than three quarters of the species alive were lost in mass extinction events, and there is mounting evidence to suggest the sixth such event may already be underway (Barnosky et al. 2011). Recent extinction rates have been calculated at between 100 to 1000 times above the historic background rate (Pimm et al. 1995), even when using an estimate of background extinction rate double that of the highest reported figure, the present extinction rate remains 100 times higher (Ceballos et al. 2015).

This pattern is not limited to a few high risk groups of species, with a mounting body of evidence that suggests current extinction rates are above historic background levels for a wide range of taxa including amphibians (Wake & Vredenburg 2008), birds (Thomas et al. 2004b; Pimm et al. 2006), mammals (Dirzo & Raven 2003; Cardillo et al. 2005), plants (Pitman & Jørgensen 2002; Thomas et al. 2004b) and invertebrates (Thomas et al. 2004b). Calculations of extinction risk are also artificially lower in poorly studied taxa due to sampling bias (McKinney 1999), and with estimates of up to 86% of species on earth yet to be classified (Mora et al. 2011) the extent of the current biodiversity crisis may be even greater than has already been reported.

A range of factors have contributed to the high rate of extinctions in the recent past, most notably land use change (Foley et al. 2005), habitat loss (Myers et al. 2000) and overexploitation (Worm et al. 2006). However, an ever growing body of research indicates global climate change is likely to become a leading driver of extinctions over the next century, both directly and by exacerbating existing threats to species (Thomas et al. 2004b; Jetz et al. 2007; Şekercioğlu et al. 2008; Maclean & Wilson 2011; Warren et al. 2013).

To attempt to address the global decline in biodiversity a set of targets to achieve a "significant reduction of the current rate of biodiversity loss at the global, regional and national level" by 2010 was agreed by world leaders, through the Convention on Biological Diversity (CBD 2003). These targets were not achieved (Butchart et al. 2010; Mace et al. 2010; Marton-Lefèvre 2010), with most biodiversity indicators considered showing continued declines with no significant reduction in rate and some of the pressures on biodiversity monitored showing increasing trends. Renewed commitments to halt biodiversity declines were made in 2010, with revised goals and the introduction of 20 "Aichi Biodiversity Targets" (CBD 2010) calling for "effective and urgent action" to be undertaken this decade. However, analysis at the mid-term of the target period suggests these targets are again unlikely to be met (Tittensor et al. 2014). This indicates further work and greater efforts are required to halt the loss of biodiversity globally.

1.3 Vulnerability Assessments

In response to the global predicted decline in biodiversity (Pereira et al. 2010) attempts have been made to identify which species are most at risk of extinction. Vulnerability assessments have been developed to provide an objective approach to identify the members of an ecosystem most at risk from change, allowing for the prioritisation of conservation action towards them. Vulnerability assessments broadly attempt to quantify how at risk a species is of going extinct and in some cases combine this with a measure of "irreplaceability", commonly measured by endemism or taxonomic uniqueness, with a high score in either component suggesting a species is in more urgent need of conservation action than a species with lower scores (Brooks et al. 2006). Vulnerability assessments are commonly used to produce conservation status for a species, placing each assessed species on a scale from low to high risk, ensuring species can easily be compared and priority species identified. Conservation vulnerability assessments exist at a range of spatial scales, from global to national park scale (Nicholson et al. 2015). Many countries have their own conservation assessment which is used to set priorities within their own borders, and there are example of continental wide assessments in both Europe and the Americas in an attempt to 'join up' conservation actions across nations. There are also a range of taxon specific assessments, such as the UK's Birds of Conservation Concern, which compare the risks faced by species relative to others within the same taxonomic group.

The IUCN Red List of Threatened Species (henceforth 'Red List') is perhaps the most famous example of a vulnerability assessment used to produce a conservation status, assigning over 85,000 species into risk categories to aid conservation decisions and prioritise resource allocation to species most in need of action (De Grammont & Cuarón 2006; Mace et al. 2008). The process is now based on data driven objective criteria, allowing for consistent risk assignment across species and taxonomic groups and with minimal opportunity for personal opinion or politic pressure to influence the outcome of the assessment (Rodrigues et al. 2006).

However, it has been argued that this process does not deal adequately with projected future changes a species is likely to experience (Trull et al. 2018) and instead focusses only on the "symptoms of declines and not the underlying causes" (Akçakaya et al. 2014). As a result there is a mismatch between the number of species listed as threatened due to climate change under the IUCN red listing process (~10%) and the number predicted to be at increased risk of extinction due to climate change in other studies (Jetz et al. 2007; Şekercioğlu et al. 2008; Warren et al. 2013).

One possible cause for this mismatch is that species projected to undergo range shifts or range contractions under climate change scenarios have generation times that are too short to qualify as at risk under population decline criteria in the red list process, with them only being upgraded in risk category many years later. This type of scenario could allow for species with good evidence for future risk under climate change to not receive appropriate conservation measures to mitigate the negative impacts, potentially leading to extinction debt or ‘living dead’ scenarios (Tilman et al. 1994), whereby species may already be on a path towards extinction with no action taken to prevent it until it is too late to reverse or halt the decline.

1.4 Climate Change Vulnerability Assessments

To attempt to correct for the issues associated with traditional vulnerability assessments in incorporating future risk and increase the warning time they provide to implement conservation action, a range of specific climate change focussed risk assessment frameworks have been developed. A wide range of this type of assessment has emerged, with often very disparate methodologies and outputs (Pacifici et al. 2015). These studies aim to quantify this future risk a species is projected to experience and at present can be considered alongside existing vulnerability assessments when considering conservation options and priorities.

1.4.1 Components of climate change vulnerability

Generally climate change risk assessments attempt to quantify the effects of three main components of risk (or some combination of): sensitivity, exposure and adaptive capacity (Williams et al. 2008; Dawson et al. 2011), with the values for each calculated from a combination of climate envelope model projections, population dynamics and life history traits.

Sensitivity refers to the extent to which the survival, persistence or fitness of a species is dependent on prevailing climatic conditions. The greater the sensitivity of a species to climate the larger the impact of slight changes to climate will be on the fitness of the species. A wide range of factors are used to attempt to quantify sensitivity, including life history traits, physiological tolerances, interactions with other species or dependence on specific habitat types (Shoo et al. 2013; Pacifici et al. 2017).

Exposure is a measure of how likely a species is to experience climate change within its current range. It can refer to a wide range of changes to climate, including temperature rise, altered precipitation patterns, flood frequency, sea level rise and frequency of extreme weather events, and at a range of spatial scales. It is commonly scored using factors such as bioclimate envelope models, projected temperature or precipitation changes within the species range and projected changes to habitat within a species range (Dawson et al. 2011; Foden & Young 2016).

Adaptive capacity refers to the ability of a species to adapt to climate change in situ. It is usually measured using intrinsic factors such as genetic diversity, phenotypic plasticity and life history traits. It is the least commonly considered component of risk in climate change vulnerability assessments and often overlaps with the sensitivity measure (Barrows et al. 2014; Pacifici et al. 2015).

1.4.2 Assessment types

Bioclimate envelope

In the simplest form of climate based risk assessment only the exposure component of climate risk is considered, based on bioclimate envelope models to predict how a species future range may differ from that which it currently occupies. Although this type of purely correlative approach is often no longer considered to be sufficient to assess risk under climate change alone (Sofaer et al. 2018), the modelling results can still be used as an input into a more comprehensive trait or trend based risk assessment. There are a wide variety of modelling techniques and approaches available to produce bioclimate envelope models, but regardless of the technique used all attempt to produce a projected future range for a species (Araújo & Peterson 2012).

Trait-based climate vulnerability assessments

Trait-based climate vulnerability assessments are the most commonly developed methodology, and aim to use intrinsic characteristics of a species to estimate how likely they are to be at risk under a changing climate (Chin et al. 2010; Arribas et al. 2012; Gardali et al. 2012; Foden et al. 2013; Barrows et al. 2014). These assessments typically consider a range of species traits, primarily relating to ecological specialization and interspecific interactions, scoring them on a low to high scale depending on how likely they are to leave a species vulnerable to climate change. The scores for each trait input are then combined to produce a single overall vulnerability score or metric, which is then compared to a range of threshold values to determine which risk category a species falls into.

Trait-based frameworks allow for assessments of multiple species over a relatively short time frame. This rapid approach is popular with conservation organisations and practitioners, as it allows them to quickly establish management priorities and adaptation plans for high risk species. These assessment approaches do not require detailed long-term monitoring data to carry out an assessment for a species, instead they are designed to use trait inputs that are already available, or which could be scored using expert opinion. This can allow for the assessment of data poor taxonomic groups or in geographical regions with poor coverage of population or distribution monitoring data (Estrada et al. 2016).

Trend-based climate vulnerability assessments

Trend-based climate vulnerability assessments attempt to combine detailed information on recent observed distribution/abundance trends and projected future trends from bioclimate modelling, usually supplemented with some trait data or “exacerbating factors” (Thomas et al. 2011; Triviño et al. 2013; Pearce-Higgins et al. 2015a). These approaches require detailed monitoring data to calculate the recent or historic changes to a species range or population, which is unavailable for some taxonomic groups or certain regions globally. These frameworks are more similar in design and inputs required to the IUCN Red List than trait-based climate vulnerability assessments, so for many species already assessed using the Red Listing process the required data inputs already exist in the correct format, allowing the assessment to be readily extended to incorporate future risk.

There is evidence to suggest that using population or abundance trend data yields better between-species predictive power of medium-term population and distribution trends (Green et al. 2008; Gregory et al. 2009) than trait-based analyses (Angert et al. 2011; Beckmann et al. 2015), suggesting trend-based vulnerability assessments may be more appropriate to use in assessing climate risk than purely trait based methods. There is, however, a risk that trend-based assessments may not be possible for regions with poor monitoring data, limiting their potential conservation benefit globally.

Hybrid climate vulnerability assessments

Some climate change vulnerability assessments have attempted to combine trait- and trend-based risk assessments, weighting one set of inputs more heavily than the other or including trend-based data as an optional set of inputs (Heikkinen et al. 2010; Young et al. 2012; Garnett et al. 2013; Moyle et al. 2013). These approaches acknowledge the importance of trend-based data in predicting future risk, but allow for a trait only assessment to be run in the absence of this data. This allows them to achieve coverage of more taxonomic groups and regions than trend-based assessments, whilst still incorporating the detailed trend data when it is available. However, these methods are arbitrarily weighted more towards either trend- or trait- based approaches, and by allowing trend-based inputs to be omitted completely makes comparisons of outputs even within the same framework difficult.

1.4.3 Vulnerability assessment problems/limitations

There is no standardised approach between risk assessment frameworks as to which components of climate change vulnerability should be considered, and there is a great deal of variation across frameworks as to which are included. The majority of, if not all, climate risk assessment frameworks include measures of exposure and sensitivity in the calculation of risk (Pacifici et al. 2015), but a much smaller proportion of frameworks consider adaptive capacity. There are also widespread differences in how the components of risk are combined across risk assessment frameworks, with a range of broad equations utilized (Foden & Young 2016). The biggest difference in equation types used by risk assessment frameworks is how the components of risk are combined, either additively or multiplicatively. There is often little explanation or justification given as to why one method was chosen over the other, despite the large impact the equation type can have on the overall calculation of risk (Dawson et al. 2011).

In addition to the inconsistency across risk assessment frameworks in which broad components of vulnerability they include and how they combine them, there are a multitude of differences in terms of which input variables are included within those categories. For instance, dispersal capacity is treated as a component of sensitivity in several studies, but as a component of adaptive capacity in others. There are also large discrepancies between the traits considered important to assessing risk within each risk assessment. Habitat sensitivity and climate tolerances appear almost uniformly across the suite of risk assessment frameworks, highlighting their perceived importance as indicators of risk under climate change, but the majority of variables appear in only a single framework. It is clear that different individuals place differing levels of importance on traits and their impact on vulnerability, but there is a lack of evidence to quantify the relative importance of these traits or evidence to justify why they have been included in the framework at all (Chessman 2013).

Differences also appear in terms of how risk is reported, either as an absolute species specific outcome or as a relative risk compared to other species assessed at the same time using the same framework. Risk assessment frameworks that generate a relative risk output require the analysis of a large number of species from a taxonomic group to be carried out in order to produce meaningful category boundaries within which to assign a species to, which is a major limitation in terms of both time and effort required on the part of a user, and all but totally prevents someone with an interest or expertise in a specific species or subset of species from undertaking the assessment process. With many of the variables in the risk assessments dependent on expert knowledge, it is counter intuitive to limit the ability of experts within a field to contribute to the process directly. Risk assessments are also a useful tool for conservationists or people undertaking conservation management ‘on the ground’ and by restricting them to not be able to run assessments for only species of management concern, the implementation of timely conservation measures for vulnerable species may be delayed.

Another major area of inconsistency in the approach of climate change risk assessments is in how they deal with uncertainty of the traits values used. The majority of the studies do not include any estimate of uncertainty, and simply assign a risk category with no confidence level attached. Of the studies that do include an estimate of confidence in the assessment process, the most common approach is to quote the confidence level alongside the risk category the species was assigned. In this way an assessment of high risk and high confidence can be given greater credence than an outcome of high risk and low confidence, although any decision on how this influences conservation management decisions taken is left up to the end user. Only one of the assessments integrated confidence estimates into the calculation and assignment of risk category (Thomas et al. 2011), meaning low confidence in numerous values entered into the assessment would result in a more conservative risk category assignment than using the same values with a high confidence. This helps to reduce burden of interpretation placed on users of the assessment, who are not required to consider two similar outcomes with differing levels of confidence.

None of the approaches to confidence used in any of the assessments can take account of the more complex and finer scale possibility when dealing with confidence levels of different traits considered together. For instance, in a situation where two trends individually have low confidence but are both showing the same direction of change should be treated as having better confidence than two trends with low confidence but showing opposite directions of change. None of the risk assessments identified are set up to account for this sort of possibility, either summing confidence scores or taking an average value whilst treating each value independently of the others. Improving how uncertainty is dealt with within climate change risk assessment will be an important area of development, particularly if they are to be implemented alongside the existing IUCN red listing process. As with any process that aims to make projections regarding the potential future state of a species the results need to be robust in order to ensure outcomes are taken seriously and potentially vulnerable species receive appropriate consideration for conservation management.

Although climate change vulnerability assessments have been used to assess multiple species across a range or geographic regions and scales, none have been tested or validated to assess how well they perform in predicting future risk (Pacifici et al. 2015; Foden & Young 2016). Some of these frameworks have already been used to assess species and inform conservation management actions and priorities, with no understanding of how informative the results of the assessment actually are. This lack of validation combined with the wide range of disparate climate risk assessment methodologies available means that it is presently very difficult to select an appropriate assessment to use and even harder to interpret results from any assessment in a meaningful way. Assessing the performance of climate change vulnerability assessments is an area of research that is of great importance in order to inform conservation practitioners and policy makers of which risk assessment approach is most robust and should be used to inform any decision making and prioritisations of species in the future (Foden & Young 2016).

1.5 Spatial prioritization

One of the most important conservation management tools being utilised to address continued declines of biodiversity around the world is the designation and management of protected sites (Watson et al. 2014). The strict definition of a protected areas is “a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values” (Dudley 2008) and although the level of protection can vary across sites they all aim to provide areas where biodiversity can survive and thrive.

The protected area network covers approximately 15% of terrestrial land, 13% of coastal/marine areas and 5% of the ocean globally (UNEP-WCMC & IUCN 2016). This network of protected sites is estimated to protect on average ~19% of terrestrial species’ distributions globally (Montesino Pouzols et al. 2014) and within Europe the figure rises to close to 25% (Kukkala et al. 2016), highlighting the importance of this network for species conservation. The importance of protected areas has been acknowledged by governments around the world, with one of the Convention on Biological Diversity‘s Aichi Biodiversity Targets being to increase the global coverage of terrestrial and inland water protected sites to 17% of the total land surface (CBD 2010).

However, despite the understanding of the importance of protected areas for halting biodiversity losses, nature conservation has always been, and is unlikely to cease being, highly resource limited; be it through constrained finances, limited time budgets or limited geographical space (Balmford et al. 2000). As such, it is not possible to protect every area that is important for biodiversity and difficult decisions must be made about where we do conservation. Determining where geographically will provide the best return on investment in conservation action, in terms of reductions of biodiversity loss, is a key challenge for policy makers and conservation practitioners across the globe.

In order to identify which areas will provide the most benefit by protecting them, effectively performing a conservation ‘triage’ (Bottrill et al. 2008), systematic conservation planning options have been developed to provide formal assessments of where conservation should be carried out geographically (Margules & Pressey 2000). Systematic conservation planning approaches aim to assess the importance of every cell within a target area, producing a ranking from most to least important in terms of protecting biodiversity across the landscape, using spatial prioritisation software tools such as Zonation (Moilanen et al. 2005) and Marxan (Watts et al. 2009).

These formal approaches to spatial prioritisation allow for multiple ways to select which cells are most important, primarily either based on species richness within each cell or by using complementarity based measures to ensure each species within the landscape has at least some proportion of its range protected somewhere. They also allow for weighting of species within the prioritisation process, so species already of conservation concern or considered valuable/important for any reason can be given higher priority over other species within the ranking process. Prioritisations can be performed on both current known distributions of species, as well using modelled future projected distributions for species under different climate or land use change scenarios.

Most spatial conservation planning is based on existing distributions of species, with little consideration given to future suitability despite it being possible to incorporate into the planning process (Wilson et al. 2006; Pressey et al. 2007). With global climate change driving widespread shifts in species distributions, the locations of highest conservation value may not remain static which may have important implications for the effectiveness of current conservation management actions. It is possible that prioritising for areas which are currently of high biodiversity value would be less effective than protecting areas of lower biodiversity now, but that are likely to increase in importance under climate change (Reside et al. 2017). There have been suggestions that the existing protected area network may perform worse under climate change, with species shifting their distributions out of existing protected sites (Hannah et al. 2007; Hole et al. 2009).

However, alongside the suggestions that species will be forced to leave existing protected areas there is also evidence that these sites may provide important benefits for new colonizing species. Protected sites have been shown to be used disproportionately more than non-protected sites by species arriving into Britain (Hiley et al. 2013), as well as providing important refugia at the trailing edge range margins of species shifting their distributions northwards (Gillingham et al. 2015). It may be the case that protected sites will perform worse for the species they were originally designated to protect, but could begin to protect new species or become important refugia for other existing species which would mean they remain as important to maintaining biodiversity as when they were originally designated.

This mixture of both potential increased and decreased utilization of protected sites under climate change poses some challenges for deciding where to continue managing existing sites and where to expand to establish new protected areas. Presently the future performance of the protected area network is often ignored by conservation practitioners and managers when making these decisions, even though understanding how projected future changes in species distributions are likely to impact upon protected sites may be crucial to minimising biodiversity losses in a changing world, and it can be accounted for within the planning process as it currently exists.

Another important issue in spatial conservation planning that is often overlooked by practitioners is consideration of the size of the landscape over which spatial prioritisation is performed, as this can greatly influence where the highest priority areas are identified. Using a small geographic boundary for the prioritisation, and including only the information on species distributions within that boundary can make species look artificially rare even if they are widely distributed over the rest of the landscape. It has been suggested that global scale prioritisations are the best practice approach to avoid this issue and to generate the most informative outputs (Brooks et al.

2006; Montesino Pouzols et al. 2014), although it may often prove impractical or impossible to include global range information in prioritisation analysis for many species. Despite this advice to plan conservation at broad spatial scales, conservation planning is most commonly performed at the national scale with only considerations for the species already present within the borders being included in the planning process (Halpern et al. 2006). This leads to important information about the relative importance of a species within a country compared to its importance at a broader regional or global scale is lost, potentially leading to duplication of effort for the same species in multiple locations or species that are regionally rare but locally common not receiving adequate protection. Addressing this issue by developing ways to incorporate the relative importance of species into national scale conservation planning could provide improvements in the overall effectiveness of spatial conservation with little to no increase in the resources required to achieve it.

1.6 Thesis aims and rationale

The main aims of this thesis are (1) to identify which species of European birds and butterflies are most likely to be winners or losers under climate change, (2) to identify where geographically across Europe species are most at risk or have the highest levels of opportunities and (3) where best spatially to target conservation resources to maximise returns on conservation investment.

Chapter 2: Climate change vulnerability for species – assessing the assessments

As a range of climate change vulnerability assessments have been developed with little guidance on which framework to select, I assess the levels of agreement between the different approaches and produce the first validation of framework effectiveness at predicting vulnerability to climate change.

Chapter 3: Extinction risks and conservation opportunities for European biodiversity under climate change

A comprehensive assessment of the future projected risk from climate change for >700 species of birds and butterflies across Europe was produced, identifying which species are most vulnerable and which are expected to benefit. I consider where geographically conservation priorities should be concentrated, as well as examining how these might shift in the future and what drives these changes.

Chapter 4: National vs Continental scale spatial conservation prioritisation for Europe

I compare the best-case continental scale spatial prioritisation against the individual nation approach that is currently used across Europe, to identify how the two approaches differ in effectiveness of protecting species distributions. I develop a rescaled version of the full continental approach that attempts to combine the benefits of both national and continental approaches and compare how well this version works against the others. I also examine how well my spatial prioritisation overlaps with our existing protected area network and examine how well that network is expected to perform under climate change.

Chapter 2 Climate change vulnerability for species – assessing the assessments

2.1 Abstract

Climate change vulnerability assessments are commonly used to identify species at risk from global climate change, but the wide range of methodologies available makes it difficult for end users, such as conservation practitioners or policy makers, to decide which method to use as a basis for decision-making. In this study I evaluate whether different assessments consistently assign species to the same risk categories and if any of the existing methodologies perform well at identifying climate threatened species. I compare the outputs of 12 climate change vulnerability assessment methodologies, using both real and simulated species, and validate the methods using historic data for British birds and butterflies (i.e., using historical data to assign risks, and more recent data for validation).

The results show that the different vulnerability assessment methods are not consistent with one another; different risk categories are assigned for both the real and simulated sets of species. Validation of the different vulnerability assessments suggests that methods incorporating historic trend data into the assessment perform best at predicting distribution trends in subsequent time periods.

This study demonstrates that climate change vulnerability assessments should not be used interchangeably due to the poor overall agreement between methods when considering the same species. The results of the validation provide more support for the use of trend-based rather than purely trait-based approaches, although further validation will be required as data become available.

2.2 Introduction

Standardised methods of risk assessment are important tools for prioritising adaptive strategies to counter the impacts of climate change, including conservation action for species most likely to face extinction. The IUCN Red List (De Grammont & Cuarón 2006; Mace et al. 2008) is globally accepted as the method for assessing the vulnerability of species to extinction. However, it has recently been suggested that this process does not adequately identify potential future risk, such as that posed by climate change, as it focuses more on the symptoms of declines than on the underlying causes (Akçakaya et al. 2014). Given that global extinction risks are high (Thomas et al. 2004a; Pimm et al. 2014; Ceballos et al. 2015) and increasing as a consequence of climate change (Thomas et al. 2004b; Warren et al. 2011) this could potentially lead to an under-estimate of the risk to species. These concerns have led to the parallel development of a number of risk assessment frameworks (Pacifici et al. 2015), each of which aims to quantify the vulnerability or extinction risk of a species due to climate change.

Each framework draws on different input variables and combines them in different ways, so they are not necessarily interchangeable. To allow for meaningful interpretation of the assessments by conservation practitioners and policy makers, it is necessary to evaluate whether the results of different frameworks are in agreement with one another; and this is currently unknown (Wade et al. 2016). If the results of species risk assessments do differ, the choice of framework would affect the perceived vulnerability of different species, hence changing conservation priorities and management actions. It is also unknown whether any of the different assessment frameworks provide a projection of risk that is accurate or realistic. Therefore, it is important that the frameworks should be validated using empirical data on observed changes to the status of species to determine which methods are most appropriate to use, something that has previously been absent from the literature (Wade et al. 2016).

Climate change vulnerability assessment methodologies follow two broad approaches (Pacifici et al. 2015) trait- and trend-based. Ultimately, how the population of a species responds to environmental change is strongly influenced by the unique combination of traits possessed by each species (and those it interacts with), so trait-based vulnerability assessment frameworks have much to commend them (Chin et al. 2010; Arribas et al. 2012; Gardali et al. 2012; Foden et al. 2013; Barrows et al. 2014). Typical traits selected by these assessments include life-history information, but they may also incorporate trait data derived from distributional data (e.g. to estimate thermal limits). By contrast, trend-based frameworks (Thomas et al. 2011; Triviño et al. 2013; Pearce-Higgins et al. 2015a) may recognise the importance of traits in ultimately determining risk, but focus primarily on abundance and distribution changes (observed and projected), supplemented by some trait information to inform assessors of the likelihood that projected trends will be realised. The merit of this approach is that it focuses on the primary cause of conservation concern (population and distribution decline, in the spirit of IUCN red-listing), and side-steps the need to identify every causal trait, or how these traits combine to determine population responses to climate change. Some studies have attempted to combine the two types into hybrid frameworks (Heikkinen et al. 2010; Young et al. 2012; Garnett et al. 2013; Moyle et al. 2013), weighting one set of inputs most heavily or including trend-based data as an optional set of inputs. The ease of applying each of these frameworks depends on the availability of trait, trend and modelled input data for the taxon and region under consideration. In this regard, some frameworks have been developed with specific taxa in mind (Chin et al. 2010; Heikkinen et al. 2010; Arribas et al. 2012; Gardali et al. 2012; Garnett et al. 2013; Moyle et al. 2013; Triviño et al. 2013) particularly birds and other vertebrates, while others are generic; and they have been applied at a range of geographic scales (Table 2.1). However, they are all amenable to being scaled up or applied to different taxonomic groups with little or no adjustment.

In general, the frameworks attempt to quantify three major components (or some combination thereof) of risk: sensitivity, exposure and adaptive capacity (Williams et al. 2008; Dawson et al. 2011). All approaches, whether trait- or trend-based, explicitly incorporate measures that are intended to represent both species exposure and species sensitivity to climate change (Table 2.1) but, beyond this, there is little agreement across the frameworks on exactly which input variables to use. This arises, in part, because there is limited evidence to identify which traits are most important in determining the sensitivity of a species to climate change (Pearson et al. 2014) or exactly how climate exposure should be quantified. A range of different inputs are therefore used to assess vulnerability, using a combination of projections from distribution models, population dynamics and life history traits. These amount to 117 specific input variables across the 12 frameworks considered here, of which three-quarters are unique to a single framework; and only 5 of the 117 variables are represented in more than two frameworks (Table S2.1). Ideally, these differences would not matter and each framework would identify the same species as vulnerable, but this should be tested, not assumed. In addition to the variation in input variables used by different frameworks, there is inconsistency in whether inputs are considered measures of sensitivity, exposure or adaptive capacity. For example, metrics of dispersal are treated as indicating sensitivity (Heikkinen et al. 2010; Thomas et al. 2011; Gardali et al. 2012; Young et al. 2012; Barrows et al. 2014), or adaptive capacity (Chin et al. 2010; Arribas et al. 2012; Foden et al. 2013) depending on the framework used.

Here, I assess the utility of 12 published frameworks, using some of the best biodiversity data available. Initially, I consider whether the 12 frameworks generate consistent results; i.e. whether the frameworks ‘agree’ on which species are at risk from climate change. I also consider the current Red List assessment approach, without incorporating any future projected declines using bioclimate envelope modelling, and compare the outputs against those from each of the 12 frameworks. I then validate the performance of the 12 different frameworks by carrying out an assessment based on historic species data and compare the outcomes to subsequent, observed changes in distribution and population. For frameworks that perform well in validation, species that are classified as at risk using historical data are expected to be most likely to have declined since then.

Table 2.1: Summary vulnerability framework information. Overall vulnerability equation used by each framework, broad methodology type, taxonomic group(s) used to test the framework, and geographic scale at which the framework was tested. The Pearce-Higgins et al. 2015 framework is a simplified version of the Thomas et al. 2011 framework, excluding exacerbating factors and including only trend data.

General vulnerability equation	Framework	Methodology type	Taxon	Locality
Exposure x sensitivity	Gardali et al. 2012	Trait	Birds	California State
	Young et al. 2012	Hybrid	Molluscs, Fish, Amphibians, Birds, Mammals	Nevada State
	Moyle et al. 2013	Hybrid	Freshwater fish	California State
	Garnett et al. 2013	Hybrid	Birds	Australia
	Thomas et al. 2011	Trend	Birds, Plants, Invertebrates	Great Britain
	Pearce-Higgins et al. 2015	Trend	Birds, Plants, Invertebrates	Great Britain
Exposure x sensitivity x conservation status	Triviño et al. 2013	Trend	Birds	Iberian Peninsula
Exposure x sensitivity x adaptive capacity	Chin et al. 2010	Trait	Chondrichthyan fish	Great Barrier Reef
	Foden et al. 2013	Trait	Birds, Amphibians and Corals	Global
Exposure + sensitivity	Barrows et al. 2014	Trait	Plants, Mammals, Reptiles, Birds	Joshua Tree National Park, California
	Heikkinen et al. 2010	Hybrid	Butterflies	Europe
Exposure + sensitivity + adaptive capacity	Arribas et al. 2012	Trait	Water beetles	Iberian Peninsula

2.3 Methods

2.3.1 Exemplar and real species comparisons

The assessments of 18 species (11 birds and 7 butterflies; hereafter ‘exemplar species’, Table 2.2) and additional British bird and butterfly species were carried out based on trait and distribution data within Great Britain. These species were chosen due to the quality and availability of data for the taxa considered within this region. The exemplar species were chosen because they were the only species of any taxonomic group with both comprehensive distribution (in two or more time periods) and traits data and a northern or southern range margin lying within Great Britain (Gillingham et al. 2015). Species with range boundaries in a region are likely to be of interest when running climate change vulnerability assessments – in this case, species with a southern range edge in this temperate northern hemisphere situation should be more likely to be predicted to be at high climate risk than species with a northern range edge. All common British breeding bird and butterfly species were considered for the additional assessment, the 234 species selected being the ones for which future distributions could be modelled based on data availability.

Trait data for the real species were collected from the scientific literature and species atlas data (Asher et al. 2001; Balmer et al. 2013). Projected distribution changes were generated by applying a Bayesian, spatially explicit (Conditional Autoregressive) GAM to the bird and butterfly distribution data (Beale et al. 2014). I used only a single climate modelling approach rather than an ensemble as my aim was to test framework performance rather than produce a definitive risk assessment of the species, and including projections from multiple models would have increased uncertainty and made comparison of framework outputs more difficult. Climate data for two emissions scenarios, low (UKCP09 B1) and medium (UKCP09 A1B), corresponding to a 2°C and 4°C increase in average temperature relative to a pre-industrial baseline by 2080 were used, as limiting the global rise above baseline temperatures to 2°C is widely considered key to avoiding the worst impact of climate change on species, while current estimates suggest 4°C may be a more realistic potential change (Mora et al. 2013). Both emissions scenarios show similar patterns of climate change of increasing mean temperature and total annual precipitation, with only the expected magnitude of change different between them, and are very close to recent observed changes. This pattern of change for the key climate variables in my model is consistent across the majority of global climate models, so using alternative future climate projections would likely yield a similar pattern of relative risk across species.

For each emissions scenario, I modelled species distributions using 11 different spatially-coherent projections (SCPs), allowing me to incorporate uncertainty within each emissions scenario into the model outputs and giving projected changes based on 22 future climate datasets per species. The change in distribution for a species was then calculated under each emissions scenario by averaging across the 11 different SCPs.

2.3.2 Simulated species comparisons

To compare the outputs of the 12 risk assessment frameworks using simulated species, I generated ranges of values for 117 unique input variables (Table S2.1), covering characteristics such as species traits and population trends. I then drew values for each input variable to generate 10,000 combinations of ‘trait sets’ that were used as simulated species in the assessments, in lieu of real world data for many species.

Where possible to do so, I applied constraints on the input variables to ensure logical consistency. For example, in the case of interspecific interactions, some frameworks ask broadly whether there is a dependence of a species on any interspecific interaction, whilst other frameworks require inputs relating to multiple, clearly-defined interspecific interactions. In this situation it would not make sense for the broad interaction to be scored as absent while specific interactions are scored as present. In this case the broad interaction is generated first and the scores of more specific interaction variables are influenced by that, to ensure consistent inputs across frameworks.

For continuously distributed input variables, upper and lower bounds were set based on reported values from the literature (e.g. body size, generation time) or theoretical minimum and maximum values. A value for the variable for each simulated species was then drawn from a uniform distribution bounded by those upper and lower limits. Species current distributions were simulated using the same approach, sampling a value for area occupied (in km^2) from a uniform distribution with an upper limited based on known real world distribution limits. For projected changes to species distributions under climate change, a future distribution was generated using the same process as for current distributions, and the percentage change in area between the two calculated.

The uniform distribution was chosen for all variables (equal probability for binary and categorical variables) because, for many input variables, there was little or no data available on how they might be distributed or the covariance between traits in reality (and they differ greatly between taxonomic groups), so an arbitrary selection of distribution would have been needed. Nonetheless, where there was an a priori expectation of the distribution of a trait based on the literature (e.g. logarithmic scaling of dispersal distance), the uniform draw was taken from between the transformed trait limits. The uniform distribution also allows for generation of traits covering the full range of the potential parameter space for the input variables, which was one of the main advantages of generated trait sets rather than a larger sample of real species data. The results therefore test consistency in framework performances, rather than the ‘true’ frequencies of risk (which are not known, given the differences between framework methods).

Many of the input variables are categorical, typically scored as low/medium/high or a variation thereof. In some cases it is possible to base these on a continuous variable which is then split into the different categories (e.g. dispersal distance < 1km scored as low, dispersal distance > 1km and <

10km scored as medium, dispersal distance > 10km scored as high). Where it has not been possible to generate a continuous variable to base the categorical split on (e.g. impact of climate mitigation measures – scored as low to high), the category was instead assigned randomly to one of the possible options, with an equal probability of assignment to each. IUCN Red List conservation status was required as an input to one of the frameworks and was generated using IUCN criteria A to D based on simulated traits, with no projected future changes considered. This conservation status for each simulated species was also used in comparisons of Red List risk category against risk category for each framework, and therefore informs of the relationship between climatic and non-climatic risks rather than whether the Red List could adequately take climate change into account.

2.3.3 Validation

Given the large variation in the risk categories assigned to each real and simulated species, validation is required to assess whether any of the vulnerability frameworks has any predictive power. To examine how well the different climate vulnerability assessments performed at projecting future risk I used the results of assessments based on historic species data to compare against observed recent trends in species distribution/abundance. For validation of the frameworks to produce robust results they need to be tested using reliable input data, poor quality input data will always lead to poor assessments of risk regardless of the method used for the assessment. I therefore utilized some of the best quality data available globally by selecting British birds and butterflies for the analysis.

Validations were carried out by using historically-available data to assign species to low-, medium- and high-risk categories (for each of the 12 risk assessment frameworks), as though the assessments were carried out in the past (i.e. excluding more contemporary information not available during the first time period), and then I compared recent distribution and population changes for species that had been assigned to each risk category. Assessments for British birds were based on the time period 1988-1991, to match the breeding bird atlas data (Gibbons et al. 1993). Assessment inputs based on the 'then-current' distribution/population were calculated from these Atlas data, with historic changes in distribution calculated from the 1968-1972 Atlas to the 1988-1991 Atlas (Gibbons et al. 1993). Projected changes in distribution were modelled using the 1988-1991 Atlas distribution data and future climate projections for 2080 under the medium (UKCP09 A1B) emissions scenario. Historic assessments for British butterflies were performed using the same approach, based on the 1995-99 Millennium Butterfly Atlas (Asher et al. 2001) and historic trends calculated from the previous 1970-82 national survey. Future projected distributions were modelled using the same methodology as for the bird species. A total of 181 British bird species and 53 British butterfly species were assessed based on this historic data.

In addition to the risk categorisation outputs of the assessments, observed recent trend data for distribution and population change since the assessment time period were required. For bird distribution trends, data from the 2007-2011 Atlas was used, giving the percentage change in occupied 10km grid squares between 1988-1991 and 2007-2011. Observed changes in population for birds were obtained from the State of the UK Birds report (Hayhow et al. 2015), as a percentage change in population from 1995 to 2013. Butterfly population change data were obtained from the State of the UK Butterflies report (Fox et al. 2011), giving a percentage change in population from 1995 to 2005. Although these dates partly overlap with the Millennium Butterfly Atlas (Asher et al. 2001), the population data are collected on fixed transects that are separate from the millions of independent distribution records that give rise to the Atlas maps. Distribution change data for the butterflies was not used in the analysis due to a large increase in observer effort in the latter time period, which resulted in increases in distribution that are likely to reflect increased effort rather than true changes in distribution.

2.3.4 Statistical analysis

The risk category outputs from each of the frameworks were converted to a set of standardised categories: Low/Medium/High risk (Table S2.2). Broad agreement between the frameworks was tested on a pairwise basis using Spearman's rank correlation, to establish how consistently species were assigned to the same Low/Medium/High risk categories by the different frameworks.

Rank correlation allows for a comparison of how well the different frameworks correspond across all levels of risk assignment, but a potentially more useful comparison is of how well they agree in identifying a species as high risk, based on the assumption that assessments will primarily be run to identify the species most vulnerable to climate change. To compare agreement on just high risk species, the risk categories were further simplified to a binary, 'low and medium' versus 'high' categorisation. Cohen's kappa, a measure of inter-rater reliability, was calculated to compare agreement between frameworks. The prevalence and bias-adjusted Cohen's kappa (PABAK) (Byrt et al. 1993) was used due to the relatively low frequency of species scoring as high risk.

Principal component analysis (PCA) was used to examine how much of the variation in risk assignment was influenced by certain frameworks and to identify whether frameworks of the same general type (trait, trend) showed similar patterns in risk category assignment. Risk category outputs from each framework for the 10,000 simulated species were used in this analysis.

For the validation analysis I predicted that most species at high risk due to climate change are more likely to have seen population/distribution decreases than species identified at low risk, and are unlikely to have seen increases over the period of the validation analysis. Species identified as low risk under climate change may still have declined due to non-climatic factors, but should also include increases in population/distribution over the validation period. I used quantile regression to validate framework performance, with change in distribution or abundance as the response variable and framework risk categorisation (Low/Medium/High) as the predictive factor (Cade & Noon 2003). This allowed me to consider trends in the 0.50 and 0.75 quantiles of distribution/population change instead of just the mean, which would identify if the majority of high risk species are declining as would be expected if a framework is performing well. The models were tested for significance against a null model using an ANOVA.

2.4 Results

2.4.1 Consistency between the results of different vulnerability

I first assessed risk to the 18 exemplar species using each of the 12 frameworks and a medium emissions scenario. The results of the assessments were highly variable, with no single exemplar species assigned to the same risk category by all frameworks (Table 2.2). The majority of species were classified as high risk by at least one assessment (14/18 species); yet only one species (*Tetrao tetrix*) was classified as high risk by at least half of the frameworks (Table 2.2). Pairwise Spearman's rank correlations between frameworks showed poor overall agreement in risk assignment (r_s mean = 0.17 ± 0.03, r_s median = 0.21). The ten 'northern' species, with a southern range margin in Great Britain, were classified as higher risk on average than the eight 'southern' species with a northern range limit in Great Britain, with average risk values of 1.7 and 1.4 respectively (scoring Low/Medium/High categories as 1/2/3), although only three of the eight southern distributed species were not classified as high risk by any of the frameworks (*Botaurus stellaris*, *Sylvia undata*, *Caprimulgus europaeus*) and one northern distributed species was not classified as high risk by any (*Tetrao urogallus*).

Focussing only on classification of species in the highest risk category, inter-rater reliability analysis (for high risk versus low or medium risk) produced a similar pattern to the rank correlation results, with 'weak' (McHugh 2012) agreement across frameworks (mean κ_{PABAK} = 0.51 ± 0.03, median κ_{PABAK} = 0.55). Almost exactly the same pattern was observed for the exemplar taxa when using a low emissions climate scenario: the average proportion of agreement between frameworks for the two scenarios was 95%, with only 11 changes in risk category across the two projected futures. The results for the low emissions scenario are given in Table S2.3.

The frameworks also showed poor overall agreement with the Red List assessment (r_s mean = -0.28 ± 0.03, r_s median = -0.25), and this agreement was not improved when I considered trait-based and trend-based frameworks separately (trait-based: r_s mean = -0.39 ± 0.02, trend-based: r_s mean = 0.01 ± 0.01).

I further tested the frameworks with an additional 181 British bird and 53 British butterfly species (Table S2.4) for which data were available to model GB distribution changes, under a medium emissions climate change scenario. Of these 234 species, 131 were classified as high risk by at least one framework (56%) (Figure 2.1B), with only 12 species (2 bird and 10 butterfly species) classified into the same risk category by every framework. Pairwise rank correlations showed poor overall agreement (r_s mean = 0.18 ± 0.03, r_s median = 0.17), confirming that even with a larger sample of real species with strong correlations between traits, there was little consistency across the frameworks. In addition, inter-rater reliability analysis indicated weak (McHugh 2012) agreement across frameworks when classifying species as high risk (mean κ_{PABAK} = 0.43 ± 0.03, median κ_{PABAK} = 0.61). I also ran the assessments for the 234 species using a low emissions climate change scenario, which produced the same overall pattern in risk and similar levels of agreement as for the medium emissions scenario.

All 10,000 simulated species were assessed individually using each of the 12 risk assessments. The frameworks showed broadly similar patterns in the overall assignment of risk to the real species, classifying the majority of species as low risk and relatively few as high risk (Figure S2.1). However, over 75% of the 10,000 simulated species were classified as high risk by at least one framework considered, and only 135 were assessed as high risk by more than half of the frameworks (Figure 2.1A). Overall, I found poor agreement across the frameworks in assigning risk (Figure 2.2, rs mean = 0.07 ± 0.01, r_s median = 0.04). Pairwise correlations within broad framework types were stronger than the overall pairwise correlations (between trait-based frameworks: r_s mean = 0.13 ± 0.04, r_s median = 0.08; between trend-based frameworks: r_s mean = 0.29 ± 0.12, r_s median = 0.18), but still relatively poor. There was also little difference between frameworks designed for a single taxonomic group and more generic frameworks (between taxon-specific frameworks: r_s mean = 0.09 ± 0.05, r_s median = 0.04 and between generic frameworks: r_s mean = 0.11 ± 0.03, r_s median = 0.04). Using inter-rater reliability analysis to compare agreement between frameworks in their classification of simulated species in the highest risk category only, I again found weak overall agreement (mean κ_{PABAK} = 0.55 ± 0.02, median κ_{PABAK} = 0.52). This inconsistency suggests against using a consensus of contrasting methods as the basis for prioritisation.

Comparing the outputs of the frameworks to Red List outputs also produced poor correlations (Figure 2.2: Spearman's rank correlation r_s mean = 0.04 ± 0.01, rs median = 0.01), with trait-based assessments showing weaker correlation with Red List outputs than trend-based approach types (trait based: r_s mean = 0.02 ± 0.01, r_s median = 0.01, trend based: r_s mean = 0.11 ± 0.01, r_s median = 0.13).

To investigate similarities between the risk assignments of different frameworks further, I used Principal Components Analysis (PCA) on the risk category outputs. I found distinct clusters for trait-only frameworks (Chin et al. 2010; Arribas et al. 2012; Gardali et al. 2012; Foden et al. 2013; Barrows et al. 2014) and trend-based frameworks (Thomas et al. 2011; Triviño et al. 2013; Pearce-Higgins et al. 2015a) with hybrid assessments falling between the two (Young et al. 2012; Moyle et al. 2013) (Figure 2.3, Table S2.5). This pattern is the same for the pairwise correlations between frameworks, with weak agreement overall, but stronger correlations within the five purely trait-based frameworks and within the three trend-based frameworks.

Table 2.2: Risk assessment output for exemplar real species. Low (white), Medium (grey) and High (black) risk category outputs for the 18 exemplar species assessed using all 12 climate change vulnerability assessment frameworks. Assessments were carried out at the Great Britain scale, based upon contemporary data, with modelled future distributions based upon a medium emission scenario (A1B projection for 2070-2099). Northern (N, with a southern range margin) or southern (S, with a northern range margin) distributed species are identified in the distribution column.

Birds	**Distribution**	**Chin**	**Gardali**	**Foden**	**Barrows**	**Arribas**	**Young**	**Moyle**	**Heikkinen**	**Garnett**	**Thomas**	**Pearce-Higgins**	**Triviño**
Black grouse (*Tetrao tetrix*)	**N**	Low	Low	High	Low	Low	Low	High	High	High	High	High	Medium
Capercaillie (*Tetrao urogallus*)	**N**	Low	Low	Medium	Low	Low	Low	Medium	Low	Low	Low	Low	Medium
Black-throated diver (*Gavia arctica*)	**N**	Low	Low	High	Low	Low	Low	Low	Low	High	High	Low	Medium
Common scoter (*Melanitta nigra*)	**N**	Low	Low	Medium	Low	High	Low	High	Medium	Low	Medium	Low	Medium
Red-throated diver (*Gavia stellata*)	**N**	Low	Low	Medium	Low	Low	Low	Low	Medium	Low	High	Low	Medium
Slavonian grebe (*Podiceps auritus*)	**N**	Low	Low	High	Low	Low	Low	Medium	Low	Low	Medium	Low	Medium
Bittern (*Botaurus stellaris*)	**S**	Low	Low	Medium	Low	Low	Low	Low	Low	Low	Low	Low	Low
Dartford warbler (*Sylvia undata*)	**S**	Low	Low	Low	Low	Low	Low	Low	Medium	Low	Low	Low	Medium
Nightjar (*Caprimulgus europaeus*)	**S**	Low	Low	Medium	Low	Low	Low	Medium	Low	Low	Low	Low	Low
Stone curlew (*Burhinus oedicnemus*)	**S**	Medium	Low	High	Low	High	Low	Medium	Medium	Low	Low	Low	Medium
Woodlark (*Lullula arborea*)	**S**	Medium	Low	Low	Low	High	Low	Medium	Medium	Low	Low	Low	Medium
Butterflies													
Large heath (*Coenonympha tullia*)	**N**	Low	Low	Medium	Medium	Low	Medium	High	Medium	Low	High	High	High
Mountain ringlet (*Erebia epiphron*)	**N**	Low	Medium	High	Medium	Medium	Medium	Medium	High	High	High	Medium	Medium
Northern brown argus (*Aricia artaxerxes*)	**N**	Low	Low	High	Medium	Low	Medium	Low	High	High	High	Low	High
Scotch argus (*Erebia aethiops*)	**N**	Low	Low	Medium	Medium	Low	Low	Medium	Medium	High	High	Medium	Medium
Adonis blue (*Polyommatus bellargus*)	**S**	Medium	Low	Low	Medium	High	Low	Medium	Medium	Low	Low	Low	Medium
Large blue *(Maculina arion)*	**S**	Medium	Low	Medium	Medium	Low	Low	High	High	High	Low	Low	Medium
Silver-spotted skipper (*Hesperia comma*)	**S**	Medium	Medium	Medium	Medium	Low	Low	Medium	High	Low	Low	Low	Low

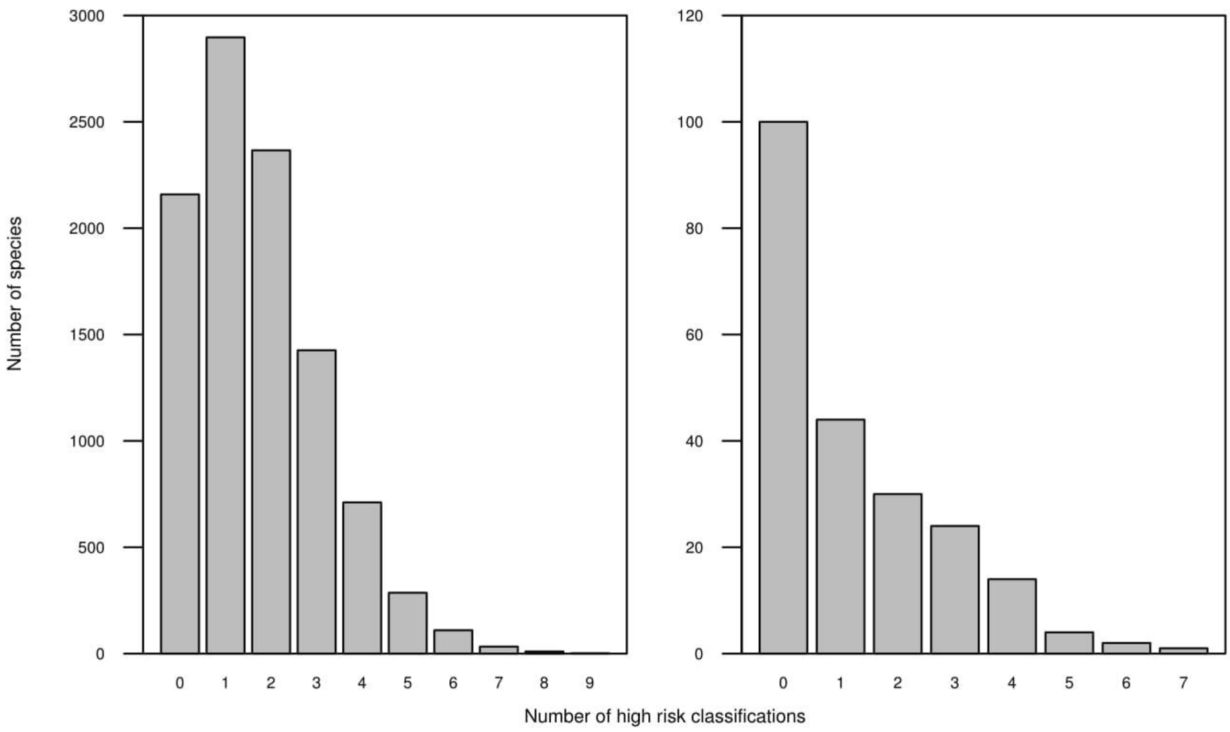


Figure 2.1: Frequency distribution of high risk classifications for a) simulated species and b) real species assessed with historic data. The number of risk assessment frameworks under which each simulated or real species was classified as high risk.

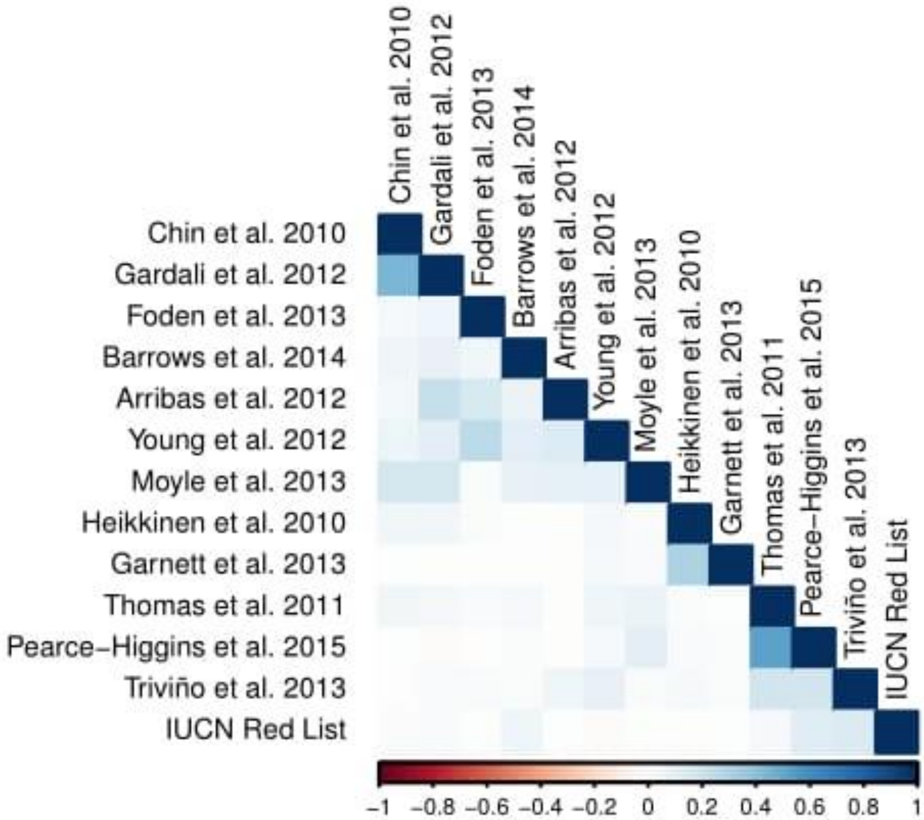


Figure 2.2: Correlation matrix showing Spearman rank correlation coefficients (r_s) for each of the 12 frameworks, pairwise against the others and the Red List outputs for the simulated species. The matrix is a visual representation of the r_s value (see x axis for range), with darker blue indicating a stronger positive correlation; using output data for the 10,000 simulated species. The correlations between each of the climate change risk assessment frameworks and the simulated Red List risk category are shown in the bottom row of the matrix.

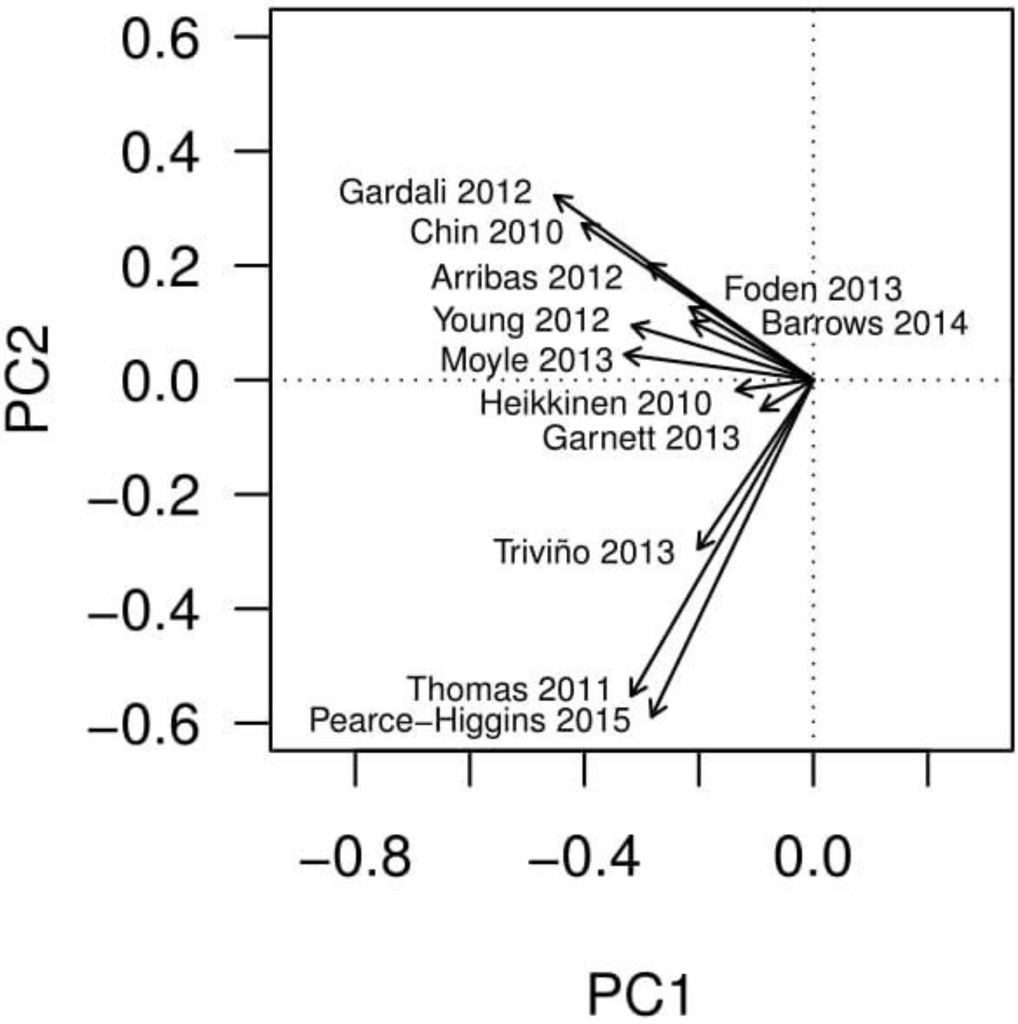


Figure 2.3: Principal component biplot. The first two principal components obtained by applying principal components analysis to the risk category outputs from the 12 frameworks for the 10,000 simulated species.

2.4.2 Validation of different vulnerability frameworks

Overall, none of the frameworks showed strong predictive power (Table 2.3), with only two of the frameworks (Thomas et al. 2011; Pearce-Higgins et al. 2015a) producing significantly better-than-random risk assessments (one significant for the 0.50 and 0.75 quantiles, and one for the 0.75 quantile, Figure 2.4). Both of these frameworks are trend-based approaches, which would suggest incorporating this type of data into the assessment process produces more robust risk outputs. The results of validation for both birds and butterflies when using population change, rather than distribution change as the response variable, also suggested limited framework effectiveness. When considering changes in bird populations, there were no significant trends in the 0.50 quantile for any of the frameworks and only a single framework showed a significant trend for the 0.75 quantile (Figure S2.2), although this was in the opposite direction to what would be expected for a framework performing well. There were no significant trends in either the 0.50 or 0.75 quantile for any of the 12 frameworks when assessing population change for butterflies (Figure S2.3), although overall performance appeared to be better than for the bird population analysis.

2.4.3 Validation using an ensemble approach

In addition to the individual framework validation, I also consider the effectiveness of using an ensemble approach to climate vulnerability assessment. I compared the modal risk category assigned to a species by the 12 frameworks against the same change in distribution/population value used in the individual framework validations. For the 181 bird species, only two had a modal risk classification of high risk, with both showing positive changes in distribution (Figure 2.5A) and population (Figure 2.5B), measured over the validation period. The 53 butterfly species also had just two species with a modal high risk classification, with one increasing its population over the validation period and the other showing little change in its population (Figure 2.5C). Therefore, the ensemble approach did not identify high risk species that subsequently declined – and across all species, there was no link between the consensus risk category and subsequent distribution trends in quantile regressions. I also considered the maximum risk category assigned by an ensemble approach (Figure S2.4), which was also not significant and would be impractical to use to set conservation priorities because maximum risk identified over half the bird and butterfly species as high risk (Figure 2.1B). When considering average risk score (again scoring Low/Medium/High categories as 1/2/3), the values for both birds and butterflies ranged from 1.0 to 2.3, with a median score of 1.3 for birds and 1.4 for butterflies. There is relatively little variation across the average risk scores, which would make prioritization based on this measure difficult due to the difficulty involved in trying to differentiate between the scores.

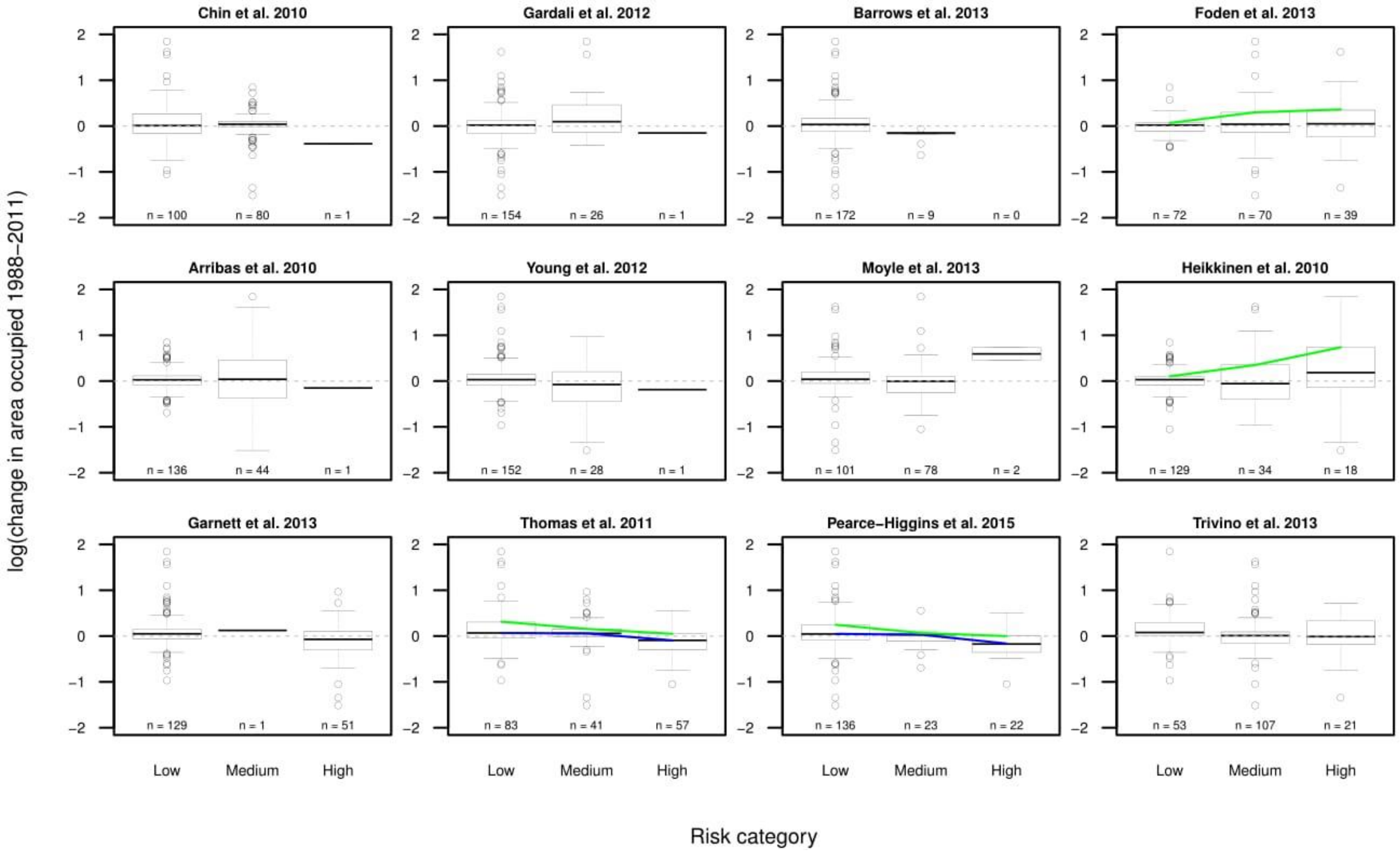


Figure 2.4: Validation boxplots showing logged change in bird distribution against simplified risk category for each of the 12 risk assessment frameworks. Blue lines show a significant trend in the 0.50 quantile and green lines show a significant trend in the 0.75 quantile. Assessments are for 181 British bird species.

Table 2.3: Summary validation trends. Directions of trends in either distribution or abundance change for birds and butterflies from low risk species to high risk species. A negative trend indicates the framework is performing as expected and a positive trend indicates poor framework performance. Significant trends are denoted with *. The frameworks are ranked first by number of significant negative trends and then by number of non-significant negative trends.

Framework	Methodology Type	Bird distribution trend direction		Bird population trend direction		Butterfly population trend direction		Correct significant trends	Correct non-significant trends	Rank
		0.50 quantile	0.75 quantile	0.50 quantile	0.75 quantile	0.50 quantile	0.75 quantile			
Thomas et al. 2011	Trend	-*	-*	-	-	-	-	2	4	1
Pearce-Higgins et al. 2015	Trend	-*	-*	-	+	-	+	2	3	2
Young et al. 2012	Hybrid	-	-	-	-	-	-	0	6	3.5
Barrows et al. 2014	Trait	-	-	-	-	-	-	0	6	3.5
Garnett et al. 2013	Hybrid	-	-	-	+	-	-	0	5	5
Arribas et al. 2012	Trait	-	-	+	+	-	-	0	4	6.5
Triviño et al. 2013	Trend	-	+	-	-	-	+	0	4	6.5
Gardali et al. 2012	Trait	-	-	+	-	+	+	0	3	8.5
Chin et al. 2010	Trait	-	-	+	-	+	+	0	3	8.5
Moyle et al. 2013	Hybrid	+	+	+	+	-	-	0	2	10
Foden et al. 2013	Trait	+	+*	+	+	-	-	0	2	11
Heikkinen et al. 2010	Hybrid	+	+*	+	+*	+	+	0	0	12

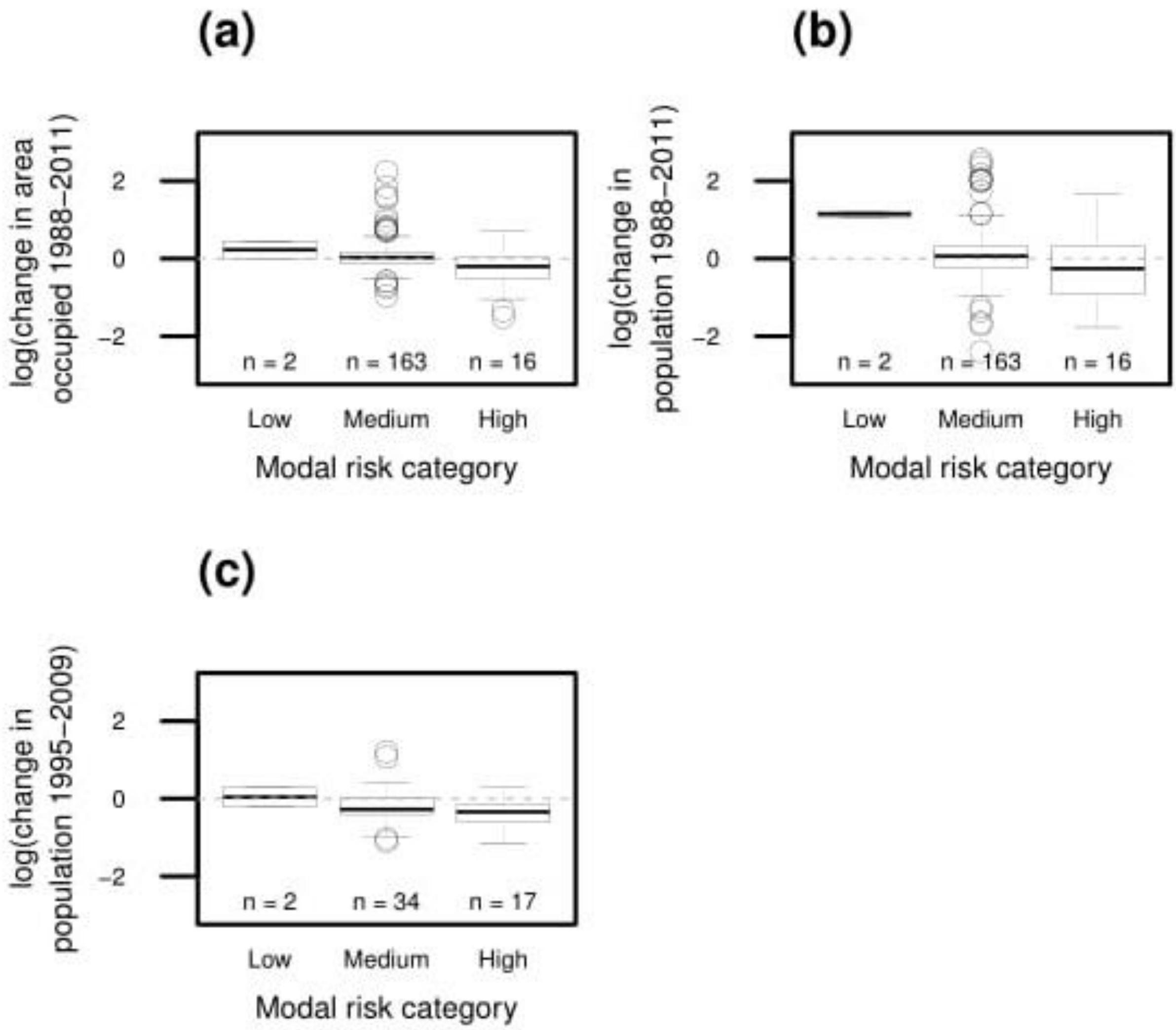


Figure 2.5: Validation boxplots showing a) logged change in bird distribution, b) logged change in bird population and c) logged change in butterfly population, against modal simplified risk category from across all 12 risk assessment frameworks.

2.5 Discussion

2.5.1 Assessment comparisons and validation

Risk assessments for both real and simulated species showed poor overall agreement across the 12 frameworks, particularly between trend- and trait-based approaches. These inconsistencies between methods hold, regardless of whether I take into account the correlated traits that exist for real species within a given taxonomic group or if I minimise correlations between traits in simulated species (given that different higher taxa possess dissimilar trait correlations), which we might expect to have caused greater inconsistencies between frameworks, depending upon the degree of similarity between the traits considered. The similarities between my results for simulated and real species suggest that the inconsistencies arise from differences between the risk framework methods themselves (i.e., which variables are included in an assessment, and how they are combined to place each species in a risk category) rather than from the test data that I used. Uncertainty in the assessments is likely to be increased if projections of future distributions from multiple modelling approaches are considered, rather than the single approach I have utilized here, suggesting that the results if used for definitive risk assessments of species could be even more variable than I have demonstrated.

Given that real and simulated species are assigned different climate-risk categories by different risk assessment frameworks, it is essential that validations are carried out to assess whether none, some or all of the frameworks have predictive power. The validation analysis here revealed that most frameworks perform poorly (Table 2.3). Only two methods (Thomas et al. 2011; Pearce-Higgins et al. 2015a), both of which were trend-based, assigned risk appropriately (i.e. the high-risk species declined more than lower risk species) and significantly (Figure 2.4); although predictions were only significant when considering change in distribution as the response variable, not change in population (top two rows of Table 2.3). One of these methods (Thomas et al. 2011) also generated non-significant predictions in the expected direction in all of the other tests (top row of Table

2.3). These two methods are closely related to one another, with both using predicted trends based on climate as the driving force, with one (Thomas et al. 2011) using additional trait/habitat information that modifies the capacity of each species to respond as predicted. These additional constraints apparently increased the predictive power of this framework.

Some of the other frameworks do show a similar overall pattern, but assign such small numbers of species to the high risk category that it was not possible to detect significant trends (see Figure 2.4). For example, one trait-based framework (Barrows et al. 2014) failed to assign any species to the high-risk category (and only between 9 and 13 to the medium-risk category) and one hybrid framework (Young et al. 2012) only assigned either one or five species to high risk across the three tests.

Two of the frameworks (Heikkinen et al. 2010; Garnett et al. 2013) classify species into risk categories based on proportions (e.g. top tenth of values assigned high risk) instead of consistently set threshold values, as seen in the other frameworks. The risk outputs from these two frameworks correlate poorly with most others, and they fall close to the origin in the PCA (Figure 2.3). Another framework (Foden et al. 2013) uses proportional cut offs for some input data and along with a method that uses proportional risk categories (Heikkinen et al. 2010) performs poorly overall in the validation analysis, with significant trends in the opposite direction to that expected if assigning risk suitably. Proportions of species at risk from climate change are not expected to be the same in different regions (or taxonomic groups), so avoiding proportional approaches is recommended.

2.5.2 Consensus assessment approach

Since each framework I tested gives markedly different results, it limits the effectiveness of using the assessments to inform conservation responses. A potential alternative is to consider the results from an ensemble of climate vulnerability assessments. The high variability in outputs, however, also limits the effectiveness of taking an ensemble approach. I considered three possible approaches to this. The first was to consider the possibility that there are many different mechanisms of endangerment from climate change, and hence to consider a species as at risk if any of the 12 methods classified it as at high risk. This was not practically useful because the majority of species were identified as high risk using this approach. The second was to assign species to the modal class of vulnerability, which resulted in almost no species being classified as high risk. Neither approach significantly identified declining species in the validation. The third approach considered was the average risk score across the 12 frameworks, which again identified very few species as high risk and with very little variation in scores between them.

None of the outputs from the ensemble approaches offer sufficient improvement over any individual method to justify the time and effort required to collect the data to run all the assessments. Combining the results of different climate vulnerability assessments also has the potential problem of a single input variable appearing in multiple methods, which could lead a single species characteristic having an unduly large influence on the overall risk score.

2.5.3 Validation analysis limitations

It should be noted that the time period for the observed changes used in the validation analysis are relatively short for both birds and butterflies (20 and 10 years respectively), and from a period when a range of other pressures have also affected species' population in the area considered, particularly changes in agricultural management (Burns et al. 2016). There is a possibility that some species considered may be climate-threatened but not yet showing a strong negative response in distribution or population, whilst others may be limited by other factors, potentially leading to the under-estimation of longer-term framework performance. In particular, species that might be expected to be most climate threatened by changing patterns of extreme weather events, such as droughts or floods, are unlikely to have experienced the full impact of this over the time period used in the validation.

However, It would be expected that frameworks show some separation between expanding and contracting species, because both bird and butterfly communities have responded to climate change during this period (Davey et al. 2012; Devictor et al. 2012), for example by polewards range shifts (Gillings et al. 2015; Mason et al. 2015; Massimino et al. 2015). The fact that such a pattern is not seen for most assessments (and some trends are the reverse of those expected), combined with the results of the comparison between frameworks, does highlight the lack of evidence currently available to support the use of most of these frameworks. As some of the assessments are designed for global assessments of risk, there is a possibility that the poor performance is a consequence of applying them over a regional scale. As data becomes available, it would be valuable to repeat this analysis at the scale of entire species distributions, rather than on regions or subpopulations, to test this. However, these methodologies are being applied at non-global scales by researchers and practitioners (Meng et al. 2016), so the results of the validation at a regional scale remain applicable to how the methods are actually being used.

2.5.4 Future climate vulnerability assessment use

The science underpinning trend-based approaches is stronger; with increasing evidence that species distribution models, which are used to measure exposure in trend-based approaches, can retrodict recent population and range trends (Green et al. 2008; Gregory et al. 2009; Stephens et al. 2016). There remains uncertainty around identifying the key traits influencing species vulnerability to climate change (Pearson et al. 2014; Pacifici et al. 2017), which may vary widely by taxonomic group and could explain the wide range of inputs across the different trait-based assessments. Recent work (Willis et al. 2015) has advocated the combination of elements of trait-based vulnerability assessments with species distribution modelling to produce more realistic projections of future risk. This approach has already been implemented to different extents by some frameworks considered here (Thomas et al. 2011; Young et al. 2012;

Triviño et al. 2013), although the outputs of these show at best weak correlations with purely trait-based assessments, suggesting that trait-only assessments may not adequately capture the exposure component of climate risk. The two general types of assessment (trait and trend) effectively represent different paradigms, with combined approaches representing arbitrarily-weighted blends of the two.

I have demonstrated that different vulnerability assessment frameworks should not be used interchangeably when attempting to assess a species' potential future risk to climate change, because assessments made with either real or simulated species produce conflicting results. The validation results suggest there is currently less evidence to support the use of purely trait-based vulnerability assessments than trend-based approaches, although neither performed very strongly for the species', time-period and location tested, and ideally, further tests of these approaches in different circumstances, for different taxa and locations, would be valuable. Trend-based approaches are the only type of methodology shown to assign species to appropriate risk categories, particularly when this information is supplemented with additional species trait data. If this conclusion is supported by other studies in other contexts, it would restrict the assessment options available to practitioners (e.g. without long-term monitoring data, trend-based approaches will not be possible). However, if frameworks not incorporating this type of information produce highly uncertain results, their long-term value remains questionable. Without significant investment in long-term monitoring, to study change as it occurs, and in research to identify exactly what traits make a species' vulnerable to climate change, our ability to identify the species most in need of conservation attention in the face of climate change will remain limited.

Chapter 3 Extinction risks and conservation opportunities for European biodiversity under climate change

3.1 Abstract

The global extinction rate is already 100 to 1000 times the historic background and is set to increase further as a consequence of anthropogenic climate change. However, uncertainties about future risks are constraining the development of adaptive conservation strategies. Here a validated climate-change vulnerability methodology is applied to scenarios of global warming between 1.8 to 3.8°C above post-industrial temperature (RCP scenarios 2.6 to 8.5) to assess the risks and opportunities facing 380 European butterfly species and 395 European breeding birds.

The assessment shows that species with constrained geographic ranges located in cold environments (especially in montane regions of southern and central Europe, and species with limited dispersal capacities) are at greatest risk of extinction within Europe. Consequently, 49% to 68% of butterflies are at high risk, compared to 16% to 20% of birds. A majority of these species are not currently listed as threatened by other drivers, suggesting that additional conservation action plans may be required for 5 to 7 times more species than at present (most already-listed species were also classed as high climate risk).

This assessment of risks and opportunities (vulnerability assessment, models of continent-wide range shifts and systematic planning analysis) highlights the value of existing spatial priorities, potential refugial areas to target for conservation, and regions where an increased provision of new protected areas may facilitate the establishment of colonising species, especially in north-west Europe.

3.2 Introduction

Biodiversity is being lost globally at an unprecedented rate (Rands et al. 2010; Johnson et al. 2017), with current estimates suggesting extinction rates are between 100 to 1000 times the historic background rate and the earth is already experiencing a sixth mass extinction event (Barnosky et al. 2011, 2012; Pimm et al. 2014; Ceballos et al. 2015, 2017). Many different drivers have been linked to these observed increases in rates of extinction, including habitat loss, land use change and increased human population pressure leading to overexploitation of resources (Myers et al. 2000; Foley et al. 2005; Worm et al. 2006). In the face of this biodiversity crisis, there is ever increasing pressure on conservationists to identify where resources can be targeted most effectively to reduce species losses and prioritise which species have the highest extinction risk.

Conservation priorities are most commonly set using the results of species' vulnerability assessments, which provide an objective approach to identifying which species are most at risk from environmental change, with these assessments broadly attempting to assign each species to a single risk category based on the likelihood of extinction (Keller & Bollmann 2004; Collen et al. 2016). Placing each assessed species on a scale from lowest to highest risk provides a consistent and easily interpretable way for practitioners and policy makers to decide which species are most in need of conservation management or intervention. However, as most traditional vulnerability assessments are designed to incorporate the already observed impacts of environmental change and not the projected impacts of likely future change, threats such as climate change may be routinely under estimated when prioritising conservation action (Keith et al. 2014; Trull et al. 2018). With populations of many species declining and these impacts projected to accelerate as a consequence of global climate change (Scheffers et al. 2016; Pacifici et al. 2017; Harris et al. 2018; Warren et al. 2018), assessing future risk is essential if we are to establish conservation priorities to maintain global biodiversity (De Grammont & Cuarón 2006; Mace et al. 2008).

Climate change vulnerability assessments have been developed to address this issue and aim to identify the species most likely to be at risk in the future under climate change (Pacifici et al. 2015; Foden & Young 2016). With early decision making and intervention crucial to preventing the extinction of a species (Martin et al. 2012; Akçakaya et al. 2014), the improved warning time offered by climate change vulnerability assessments can help guide effective conservation management. Effective prioritisation is of ever increasing importance in a changing world and climate change vulnerability assessments are an important tool to help effectively quantify climate change threats, inform policy and limit the negative impact of climate change (Foden & Young 2016).

With climate change predicted to lead to a redistribution of species (Thomas & Lennon 1999; Hickling et al. 2006; Huntley et al. 2006; Chen et al. 2011), there is a need for spatial prioritisation using projected species distributions to identify where conservation should be done to best protect biodiversity long term (Pressey et al. 2007; Shoo et al. 2013). With different management options available depending on if a location provides a refugia for species already present or if it needs to be prepared for the arrival of new colonisers (Gillson et al. 2013; Brambilla et al. 2018), identifying what is driving the increasing importance of a location under climate change can provide valuable insight for on the ground management of an area.

Here, a climate change risk assessment framework (Thomas et al. 2011), shown previously to predict historic population and distribution trends (Wheatley et al. 2017), is used to assess the vulnerability of 395 European bird and 380 European butterfly species under three climate change scenarios for 2080-2100. Climate risk scores are compared with current assessments of species vulnerability, allowing us to identify a set of species which are presently not of conservation concern but are likely candidates to require action over the course of this century. A spatial prioritisation analysis for Europe is also used to identify new priority areas for conservation in regions where the climate is projected to ‘improve’ from the perspective of each species, and the drivers of increasing priority are examined.

3.3 Methods

3.3.1 Climate Change Vulnerability Assessment

To assess the vulnerability of the chosen species to climate change a trend-based risk assessment was utilised (Thomas et al. 2011; Wheatley et al. 2017), which allows me to identify opportunity under climate change as well as risk. The framework scores four components of climate change impacts on a species: observed recent decline of population or distribution, projected decline within a species existing range, observed recent expansion outside a species range and the projected expansion outside a species existing range. Each of these components is primarily based on the decadal rate of change in the species distribution or population, supplemented with additional information on potential exacerbating or mitigating factors, such as a species having limited dispersal ability or limited habitat availability within its projected distribution. The scores for the two decline components are then combined into a single score and the two expansion components are also combined into a single score.

Projected changes in distribution for both taxonomic groups were derived from species distribution models (next section) and converted to decadal rates of change. Current trends in population for the bird species were calculated from the change between 1990–2000 (BirdLife International 2004) and the most recent 2010-2015 estimate (BirdLife International 2015), and again converted to a decadal rate of change. Data on exacerbating factors for the bird species was collected from a variety of sources, including the IUCN Red List and European Red List assessments (BirdLife International 2015, 2016), the Handbook of the Birds of the World Alive (del Hoyo et al. 2016) and the scientific literature where available and applicable. Data on exacerbating factors for the butterflies was collected from the IUCN Red List and European Red List (van Swaay et al. 2010, 2016), the Climatic Risk Atlas of European Butterflies (Settele et al. 2008), the Butterflies of Europe and the Mediterranean area (Tshikolovets 2011) and the scientific literature where available and applicable.

3.3.2 Species Distribution Modelling

To model the future distributions of each species I applied a Bayesian hierarchical, spatially explicit (Conditional Autoregressive) Generalised Additive Model to species' distribution data. This method allowed me to separate climatic, spatial and random components determining the distribution of each species and to account for potential spatial autocorrelation in the distribution data (see below) (Beale et al. 2014). Where data were available to do so, distributions were modelled at two spatial scales - the entire Western Palearctic biogeographic region (30-75°N, -15-65°E) and Europe (35-72°N, -15-30°E). Under future climate change, Europe is projected to experience climatic conditions outside the range of conditions currently observed, although these conditions are found in the Western Palearctic. As many of the species considered in the risk assessment have ranges that extend beyond the European boundary, they may already survive and persist within the future conditions that would be novel for Europe. By including this information, the risk of overestimating the magnitude of potential changes to species distributions is reduced.

For species with Western Palearctic data, models were initially constructed using uninformative priors (i.e. no prior expectation of what the covariate relationships should be) to describe the relationship between occurrence and climate at a broad spatial resolution (1 degree). A second model was subsequently fitted to the finer-scale distribution data from Europe using informative priors generated from the Western Palearctic scale analysis. As a result, any strong climatic signal based on the Western Palearctic distribution would remain essentially unchanged when modelled using European data only, unless the climatic signal within the European distribution was markedly different. In cases where there was uncertainty in the estimation of species' responses at a Western Palearctic scale, then the finer scale model would be more heavily informed by outputs from the European component of the model. For species endemic to Europe, it was only possible to model at the finer spatial scale using uninformative priors, but as this describes the entire global range of the species this analysis is appropriate as any novel climatic conditions experienced across Europe would also be outside the range of conditions endemic species are currently found within. To attempt to control for variation in recorder effort across the current distribution data and between taxonomic groups, I included a measure of observer effort for each grid cell in the model, calculated as the proportion of species observed in a cell relative to the number of species expected to occupy the cell. Expected species richness was generated using FRESCALO software (Hill 2012), which compares the number of observed species in a cell against those found in a compositionally-similar nearby neighbourhood of cells. I considered the proportions of different habitat types within each cell as the measure of compositional similarity, based on the Corine Land Cover 2006 dataset, with the FRESCALO process implemented in R using the 'sparta' package (August et al. 2015).

For the bird species, European distribution data were obtained as a 50 × 50 km UTM grid from the European Breeding Bird Census Atlas (Hagemeijer & Blair 1997), with distribution data for the Western Palearctic obtained from species range polygons (BirdLife International & NatureServe 2015) rasterized to a 1 degree resolution. For the butterfly species, European distribution data were obtained as a 0.5° × 0.5° grid from the Distribution Atlas of Butterflies in Europe (Kudrna et al. 2011) and Western Palearctic distribution data from GBIF records and polygon data (Tshikolovets 2011) again rasterized to 1° × 1° spatial resolution.

A combination of four bioclimate variables were used in the model: mean temperature of the coldest month, growing degree days above 5°C, the coefficient of variation of temperature and soil moisture. These variables are commonly used to model species distributions, particularly for birds and butterflies, and are likely to have direct physiological impacts on the species as well as indirect effects on vegetation utilized by the species (Crick 2004; Araújo et al. 2005; Huntley et al. 2008; Heikkinen et al. 2010; Beale et al. 2014). To calculate the bioclimate variables, monthly data for mean temperature, precipitation and cloud cover were required, in addition to soil available water content data. Current climate data was obtained from the CRU TS3.10 gridded dataset (Harris et al. 2014) at 0.5° × 0.5° resolution.

For future climate I considered three potential Representative Concentration Pathway (RCP) trajectories which are referred to as low, medium and high future climate change - RCP2.6 (low ~1.11°C warming) , RCP4.5 (medium ~1.51°C warming), RCP8.5 (high ~2.11°C warming), with all temperature increases for Europe relative to a 1980-99 baseline. Climate variables associated with each future trajectory of change were produced by pattern-scaling spatial fields of changes (Osborn 2009) in monthly climate from the HadGEM2-ES model from the CMIP5 model set at 0.5° × 0.5° resolution and averaged over the 2070-2100 time period. Soil available water content data were obtained from the ISRIC-WISE global data set of derived soil properties, at 0.5° × 0.5° resolution (Batjes 2005).

3.3.3 Spatial prioritisation

A spatial conservation prioritization for Europe was performed on a 0.5° × 0.5° resolution for both birds and butterflies using Zonation v4.0 software (Lehtomäki & Moilanen 2013). I used the core-area zonation (CAZ) analysis variant of zonation, which is weighted more towards complementarity than species richness, to produce priority area maps iteratively ranked from lowest to highest priority for conservation. Species were weighted according to their climate change vulnerability score (1 to 6, from high opportunity to high risk), so high risk species were considered as higher priority targets during the ranking process. To identify if changes in priority were driven by continued presence of species or colonising species arriving into a cell, I calculated the cell weighting of each species as assigned by Zonation during the prioritization process. This then allowed me to identify which species was the most important contributor to the cell's priority rank during both the current and each of the future prioritizations and compare between the time periods. If the same species was the most important in both time periods or changed to a species already existing in the cell (starting probability of occupancy > 0.5), the driver of change within the cell was considered to be 'refugia'. If the most important species changed to one not previously found within the cell or with a starting probability of occupancy < 0.5, the driver of change within the cell was considered to be ‘colonisation’.

3.3.4 Statistical Analysis

Broad agreement between my climate change vulnerability assessment and the European Red List assessment was tested using Spearman’s rank correlation, to establish how consistently species were assigned to similar levels of risk by the two approaches. To further compare agreement on the most vulnerable species between the European Red List and the climate change vulnerability assessment, the risk categories were simplified to a binary, ‘not threatened’ or ‘threatened’ categorisation. For the Red List the categories Vulnerable, Endangered and Critically Endangered were considered to be ‘threatened’, and for the climate risk assessment only the High Risk category was considered as ‘threatened’. Cohen’s Kappa (Byrt et al. 1993), a measure of inter-rater reliability, was then used to compare agreement between the two assessments, as well as calculating the raw proportion of agreement between the two approaches.

To identify the relationship between climate risk score and properties of species existing distribution a multinomial log-linear model (function “multinom” from the R package “nnet”) was used, with climate risk score as the response and mean temperature of the species range and total range size as predictors. I used the results of the model for all species of birds and butterflies to predict the highest probability risk category at any point across the entire possible parameter space of range size and mean temperature of the range. I then calculated the same predictor variable values for all species of birds and butterflies in Europe that were not able to be assessed fully using the climate change vulnerability assessment framework, allowing me to use the results of the multinomial model to infer the possible level of climate change threat to which each of these species may be exposed.

All analysis was conducted in R v.3.3.2 (R Core Team 2016).

3.4 Results

3.4.1 Climate change vulnerability assessment

Between 66% (17% medium risk, 49% high risk) and 73% (4% medium risk, 69% high risk) of European butterfly species are threatened by climate change, depending on the emissions scenario, and 35% (19% medium risk, 16% high risk) to 48% (29% medium risk, 19% high risk) of birds are threatened (Figure 3.1; Table S3.1). Similar percentages of bird species are expected to benefit from climate change, ranging from 44% (15% medium opportunity, 29% high opportunity) to 51% (17% medium opportunity, 34% high opportunity), but in comparison only between 19% (5% medium opportunity, 15% high opportunity) and 27% (5% medium opportunity, 27% high opportunity) of butterflies are likely to benefit.

The proportion of high risk species increased only modestly with increasing climate change (Figure 3.1): a total of 91 bird and 270 butterfly species were identified as high risk under at least one of the climate change scenarios considered, with 61 and 176 of those consistently classified as high risk under all three of the climate scenarios (full species lists and risk categories under each climate scenario are provided in Table S3.1).

I examined the influence of the two characteristics of species distributions, total size of the geographic range and average temperature of the environment within the range, on overall climate risk for species (Figure 3.2a). A combination of small geographic range size and relatively cold environments is a strong indicator of high climate risk, while species with small geographic ranges but in relatively warm environments were more likely to be a mixture of risks and opportunities. Species with large geographic ranges currently tended to show limited impacts from climate change, or opportunities for further expansion with very few at any level of climate risk.

With the known range properties and climate risk categories for each of the species assessed, I used multinomial log-linear models to generate a probability surface across the entire parameter space of range size and mean range temperature combinations, identifying the most probable risk category at each position (Figure 3.2b). These results show that the vast majority (93% of 167 unassessed butterfly species; 75% of 78 unassessed bird species) are also likely to fall into the high risk category.

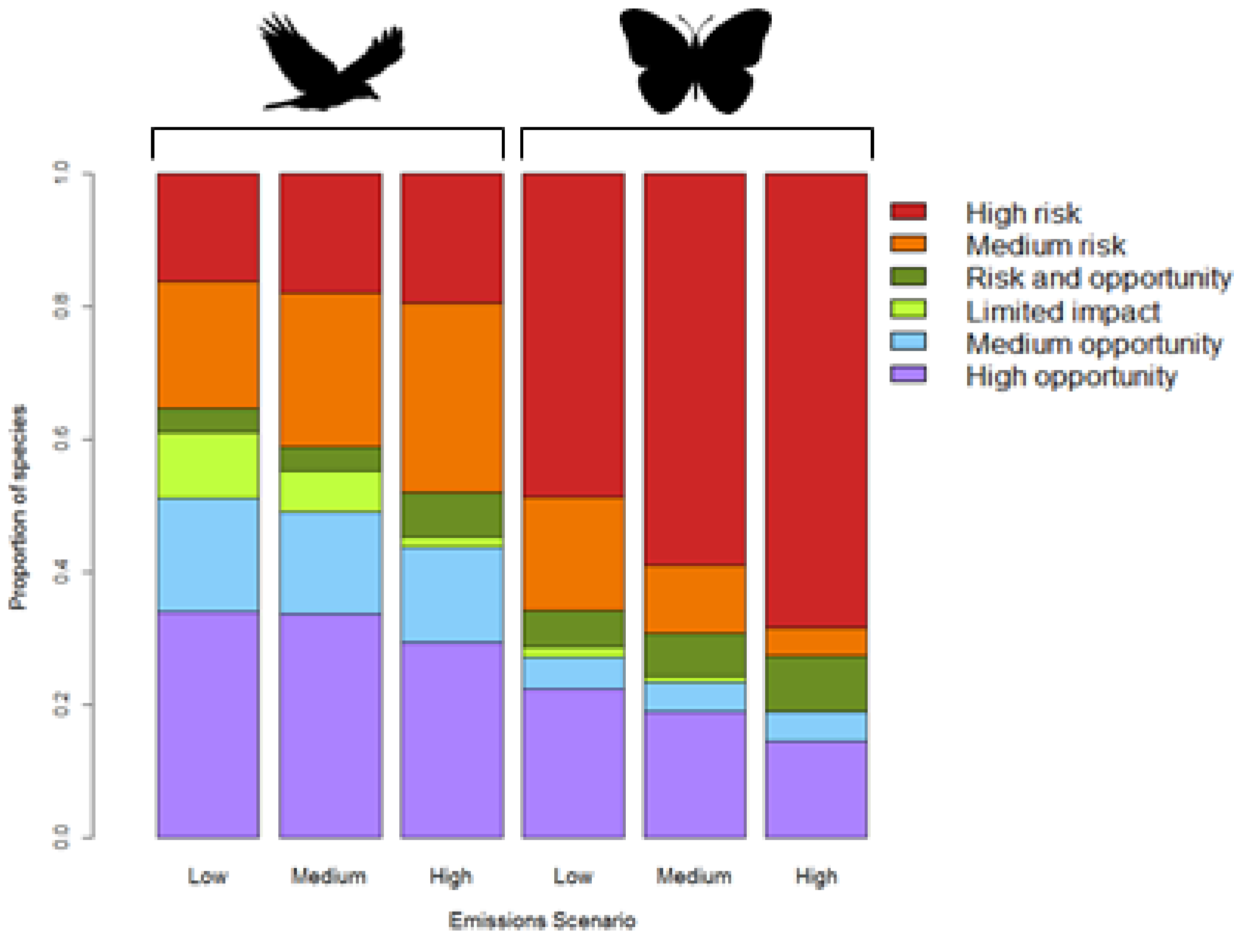


Figure 3.1: Comparison of climate vulnerability score distributions for birds and butterflies. The proportion of European bird and butterfly species classified into each risk category by the climate vulnerability assessment, under each of the 3 emissions scenarios considered.

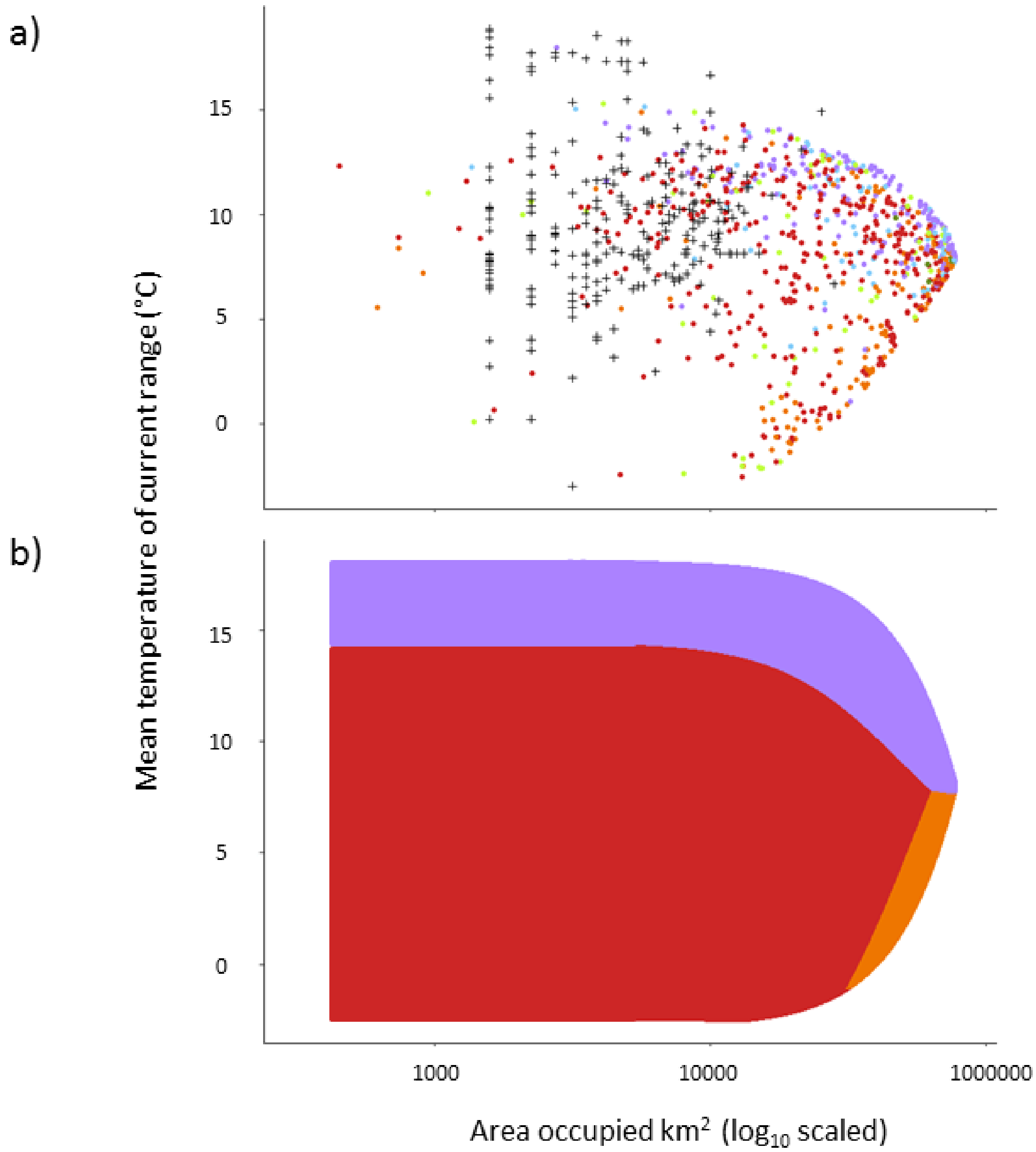


Figure 3.2: a) Individual species climate risk score (based on the high climate scenario) and b) modelled highest probability climate risk score, based on range size and mean temperature of the range for each species of bird and butterfly. The black crosses represent species already present in Europe but which could not be formally assessed by the climate change vulnerability assessment, primarily due to small range size., to demonstrate where they might fall on the climate vulnerability spectrum. Polygons show the most likely risk categorisation resulting from the multinomial model of climate risk score against area occupied and mean temperature of the species range. Of the 6 possible risk categories only 3 are modelled to be the most likely over all the possible parameter space - high risk (red), high opportunity (purple) and medium risk (orange).

3.4.2 Red List comparison

Focussing on those species that are currently on the European Red List (i.e., existing priority species), the majority (62%) are also at risk from future climate change (Figure 3.3), suggesting that climate change represents an additional threat to species already of conservation concern. Despite the high climate risk to already-listed species, there is only a relatively weak correlation between the climate vulnerability assessment category and the Red-list category of each species (Least Concern through to Critically Endangered), for all climate change scenarios (Figure 3.3: r_s 0.22 - 0.27 for birds, r_s 0.10 - 0.12 for butterflies, all significant at $p < 0.05$). However, looking across all species, whether currently threatened or not, Cohen's Kappa inter-rater reliability analysis indicated only 'weak' agreement for birds and 'no' agreement for butterflies: most butterflies are currently not listed as threatened, while climate vulnerability analysis places 49% to 68% as being at high risk. The majority (72% of birds; 86% of butterflies) of climate-threatened (medium or high risk) species have not previously been recognised as threatened at all, and they represent additional species of conservation concern at a European scale.

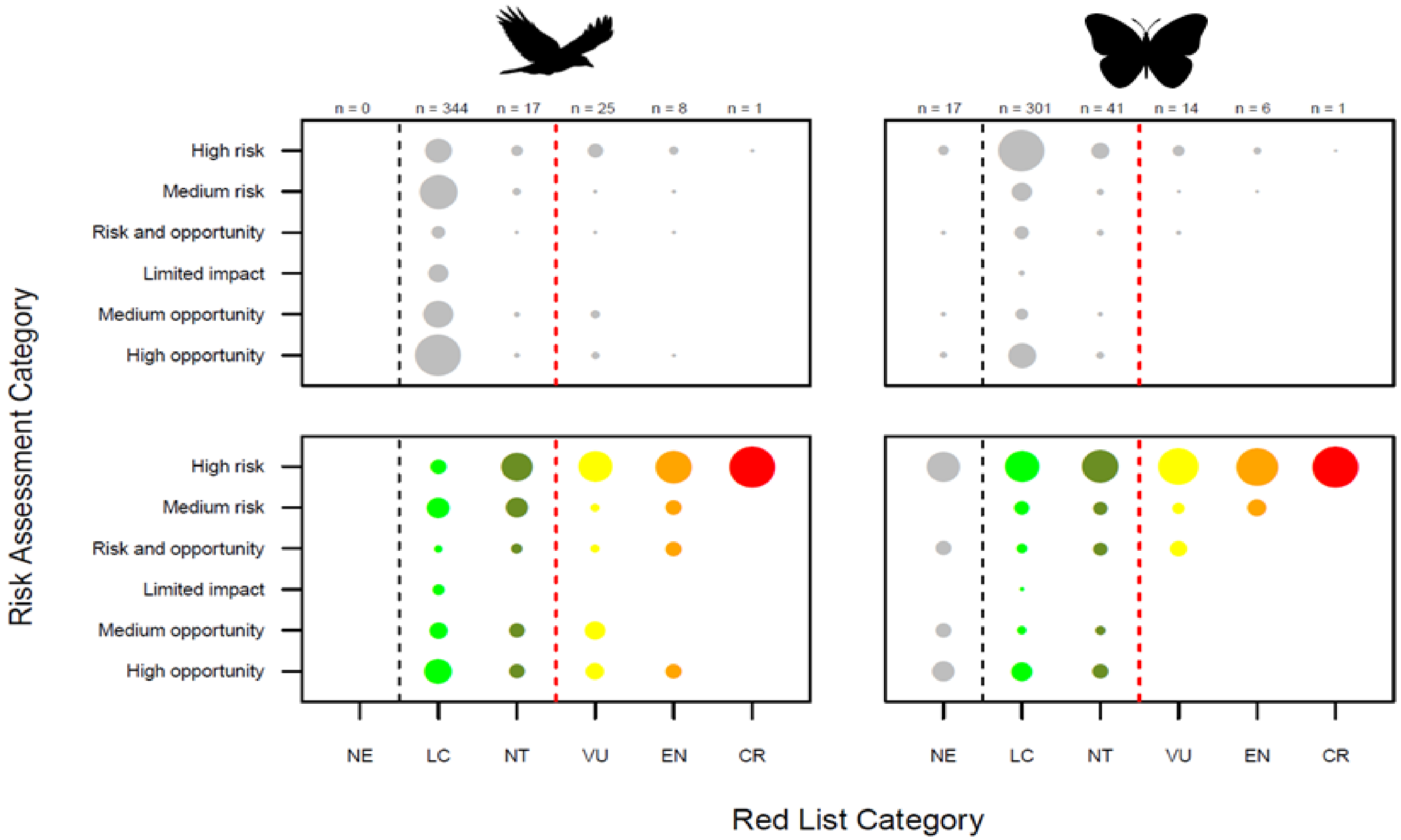


Figure 3.3: Comparison of European Red List risk category and climate vulnerability category for birds and butterflies. The proportion of species classified into each risk category by the climate vulnerability assessment, against their current European red list assessment risk category (NE - Not Evaluated, LC - Least Concern, NT - Near Threatened, VU - Vulnerable, EN - Endangered, CR - Critically Endangered). Scaled by total number of species (top panels, grey circles) and scaled by number of species within each red list category (lower panels, coloured circles). Red list categories to the right of the red dotted line are considered to contain currently-threatened species. As assessed using a high emission RCP 8.5 scenario.

3.4.3 Spatial Prioritization

Using the complementarity-based Zonation approach (Moilanen et al. 2005; Montesino Pouzols et al. 2014), conservation priority areas based on species current distributions were relatively insensitive to whether I considered all species (equal weighting to all species; Figure 3.4a), weighted higher for existing European Red List species (Figure 3.4b), or included additional weighting, based on each species' climate risk score (Figure 3.4c; Red List weighted vs. unweighted rank correlation: birds $r_s = 0.85$, butterflies $r_s = 0.89$; climate weighted vs. unweighted rank correlation: birds $r_s = 0.92$, butterflies $r_s = 0.98$). Regardless of how species were weighted, core priority areas for conservation remained unchanged (for their current distributions), and are important to protect for reasons of both current and anticipated future threats; species need to survive where they already are if they are to persist long enough to shift their distributions in future. Furthermore, although distribution patterns differed substantially between birds and butterflies (Figure S3.1), current priority areas for both taxa were broadly similar, highlighting the importance of northern Fennoscandia, much of the Mediterranean and significant mountain chains (Figure 3.5a: $r_s = 0.48$, $p < 0.001$).

Projected distribution shifts, on the other hand, suggest that climate change will add important new priority areas for conservation in north west Europe (Figure 3.5c) to those assessed from current distributions. Again, there is a high level of agreement about future priority areas when comparing birds and butterflies (Figure 3.5b: $r_s = 0.47 - 0.62$, all significant at $p < 0.05$). This pattern is consistent with polewards shifts in distribution under climate change (Hickling et al. 2006; Chen et al. 2011; Mason et al. 2015), but the growing importance of the north west is primarily driven by new species colonising the region (Figure S3.2).

However, when examining the entirety of Europe, the retention of existing species within 50 x 50 km grid cells is the largest driver of increasing conservation priority, particularly again in the Mediterranean, southern and central mountain ranges of the continent (Figure S3.2). When considering the 50 x 50km grid cells with the largest increase in conservation priority under climate change compared to the present day (top 10% of priority changes under the high climate change scenario), 68% and 58% (for birds and butterflies respectively) were increasing in priority due to the retention of species already occurring within the cell in the current distribution.

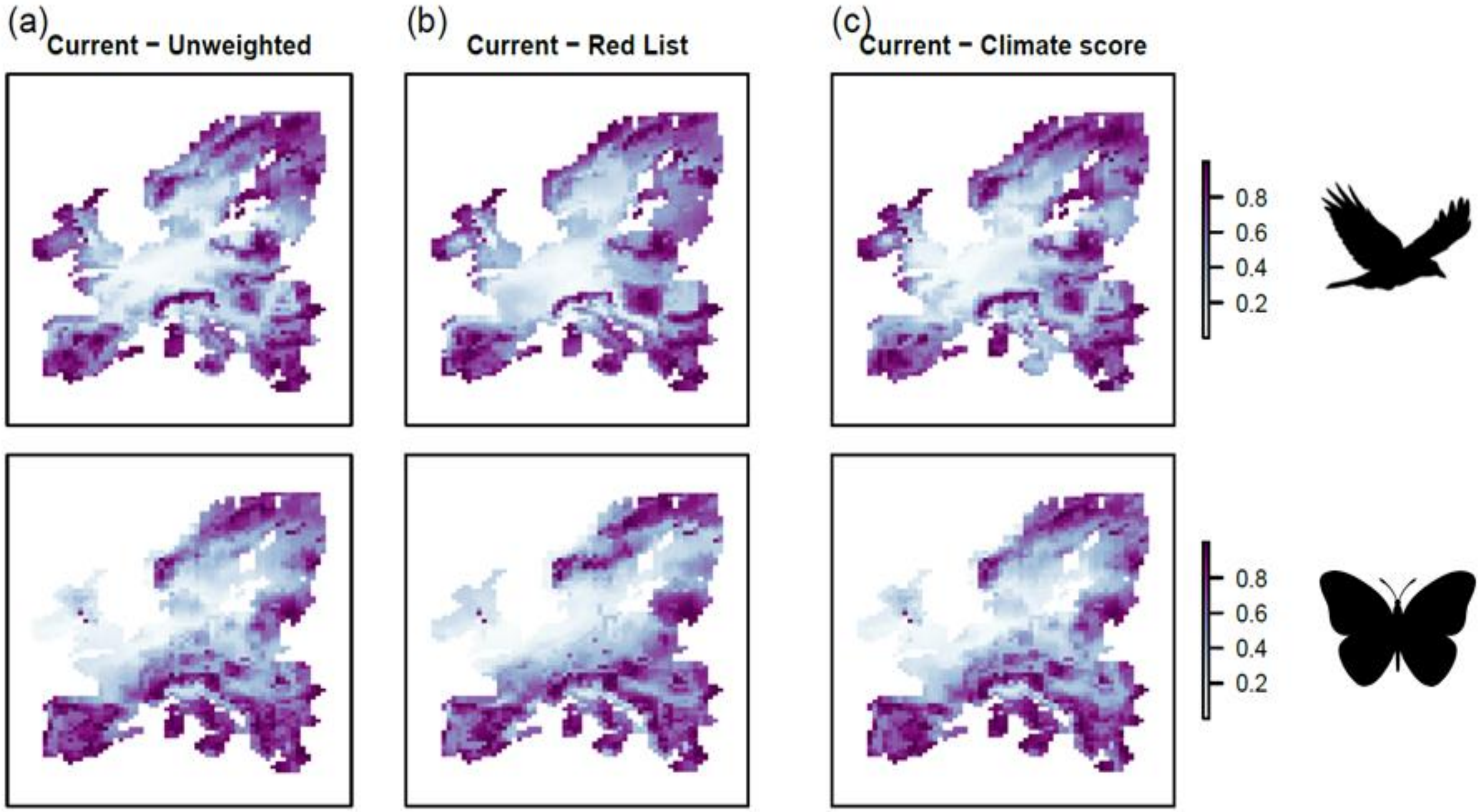


Figure 3.4: Spatial prioritization for birds (top row) and butterflies (bottom row) based on current species distributions, (a) all species weighted equally, (b) species weighted by European Red List score and (c) weighted by climate risk score (high emission RCP 8.5 scenario). Dark purple areas are highest priority cells, with white areas the lowest priority in terms of complementarity-based assessment of conservation value.

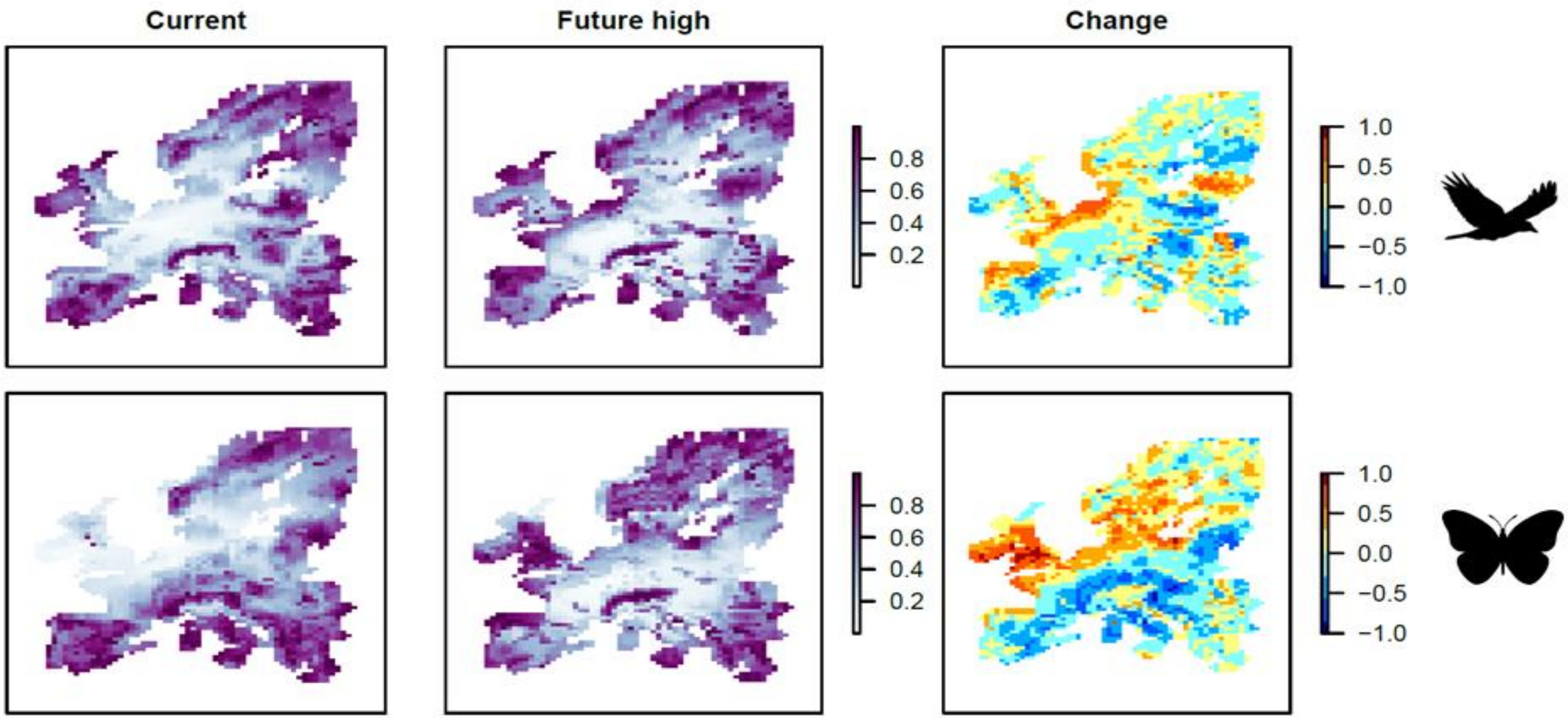


Figure 3.5: Spatial prioritization for birds (top row) and butterflies (bottom row) based on current and projected future species distributions. Dark purple areas are highest priority cells, with white areas the lowest priority in terms of conservation value. The change panels show the difference in priority between the current and projected distributions, with areas with increased priority in red and areas with decreased priority in blue.

3.5 Discussion

The overall pattern of risks and opportunities under projected future climate change vary across the taxonomic groups considered in the assessment. For the birds the overall pattern of risk is mixed, with close to a 50:50 split of risks and opportunities from climate change (Figure 3.1). The butterfly species assessed show a markedly different pattern of risk overall, under all potential climate change trajectories considered the majority of species are identified as being at high risk of extinction from the impacts of climate change. Despite the differences in overall level of risk between the taxonomic groups, with upwards of 49% of butterfly and 16% of bird species in Europe highly threatened by climate change (Figure 3.1); this represents a significant challenge for conservation across the continent, to accommodate the inevitable changes to biodiversity.

When considering both the size of species distributions and the mean temperature of the environment across that range, I find that high-risk species of both taxonomic groups tend to have small geographic ranges associated with relatively cold environments (Figure 3.2). Butterfly species, in particular, in this category are confined (endemic) to the Alps and to other southern and central European mountain ranges, and they have little prospect of being able to colonise the north of Europe (which would require descending to the inhospitable lowlands). A higher proportion of butterflies than birds have this distribution type, which explains why a much higher percentage of butterflies than birds were assessed to be at high risk. While high risk European bird species also show a concentration in the Alps, most are found in northern Europe (mainly Fennoscandia, Figure S3.3a) where climate is the most important determinant of the status of species (Howard et al. 2015), whereas butterflies with Fennoscandian distributions showed no greater risk than others (reflecting the overall much higher species richness in the southern mountains: Figure S3.3c; Figure S3.4). Species with high opportunities from climate change have wider distributions in relatively hot regions (Figure 3.2), in the lowlands of southern Europe, and are expected to be able to expand northwards in the future (Figure S3.3b&d; Figure S3.5). Using the modelled outputs of predicted risk category based on range size and mean temperature of the range, I find the majority of European bird and butterfly species I could not fully assess using the risk assessment framework are likely to also be at high risk of extinction from climate change, suggesting the headline estimates of the percentage of species at risk may even be conservative.

Although a large number of species are classified as high risk, a subset of species are expected to benefit from climate change (Figure 3.1), including a small number that are otherwise threatened by non-climatic processes. Even for species that are threatened by climate change (taking both losses and gains into consideration), many exhibit at least some potential gains in new areas: overall, 39% of butterflies and 58% of birds are expected to show some potential gains in new areas. Climate change is generating opportunities as well as increasing risks, and hence there is considerable potential to develop areas for conservation in regions of growing importance for the maintenance of biodiversity.

Recognising that between five and seven times as many species are threatened by climate change than are currently considered conservation priorities may require a re-drawing of the conservation priority map for Europe. The results of the spatial prioritisation for Europe suggest that the highest priority areas for conservation will shift under climate change, with the general pattern being a shift north-west across the continent (Figure 3.5), with southern England and Northern France particularly increasing in priority. A similar pattern of shifts is seen for both birds and butterflies, which may be due to climate buffering effects along the North Atlantic seaboard. If we are to realise the conservation potential of the north west, some re-prioritisation of land use will be required, given that parts of this region are dominated by agriculture, and therefore unlikely to facilitate range expansion or increased resilience to climate change (Thomas et al. 2012; Oliver et al. 2017).

With the majority of areas increasing in priority doing so because of their importance for species already present within them (Figure S3.4), this finding highlights the importance of conservation management to protect refugia for existing species in the face of a changing climate. This is particularly important in montane regions across Europe, where species are likely to be extremely limited in their ability to shift distributions to find new suitable climate space and managing for species already present will help to protect both them and new arrivals with similar requirements.

This analysis does not consider the possibility of new species colonising from surrounding regions. An additional 110 bird and 225 butterfly species breed in the Western Palearctic (BirdLife International & NatureServe 2015; del Hoyo et al. 2016), but not currently in Europe, representing a pool of species that could colonise in the future if Europe becomes climatically suitable for them. Under this circumstance, the net loss of biodiversity would be lower than the results of the assessment indicate is possible. Identifying and facilitating the expansion of these species could become another important impetus for conservation, in addition to attempting to protect the species already present in the region.

The results of the vulnerability assessment indicate that large numbers of species of European birds and, especially, butterflies are likely to face increased extinction risk by the end of the century as a result of climate change. Many of these species are currently not of conservation priority but are likely to require increased efforts in the future to ensure their survival and persistence. The protection of locations of current high priority should be re-doubled, whilst additional protection of areas of future colonisation should also be considered.

This analysis should be regarded as a wake-up call rather than a prognosis of despair - it should not be presumed that a species that is at high risk will actually become extinct, if we act soon enough. Improved monitoring of populations and distributions is needed so that risks assessments and knowledge of ecological needs can be improved over time (Wheatley et al. 2017), and specific climate-smart conservation strategies and actions need to be developed before it is too late.

Chapter 4 National vs Continental scale spatial conservation prioritisation for Europe

4.1 Abstract

Planning where to implement conservation management is an important decision for conservation practitioners, but it is often performed for specific regions with little or no consideration for how the scale chosen will influence the effectiveness of the landscape prioritisation. In this study I perform systematic spatial prioritisations for Europe using three alternative spatial scales; the best practice full continental scale, the commonly used individual national scale and a novel rescaling of the full continental approach. The effectiveness of each approach to protecting species distributions at different levels of landscape protection were tested, with a particular focus on the performance of each approach at the 17% Aichi target for landscape protection. The performance of the existing protected area network in Europe is tested against these systematic spatial prioritisations, both for the present day and for three projected future climate change scenarios.

The results show that spatial conservation planning applied at the broadest landscape scale possible is consistently more effective than other prioritisation scales for both birds and butterflies, both now and in the future under climate change. It confirms that the individual national scale at which prioritisation is usually performed at currently is significantly less effective at protecting species than either alternative approach tested here. Comparisons of these spatial prioritisations with the existing European protected area network suggests that under climate change sites currently designated for protection are likely to become increasingly important in preventing the loss of species across the continent.

This study demonstrates that spatial conservation planning in Europe should not focus on individual countries separately; including information on the relative importance of species across the continent would significantly improve the returns on conservation investment. The existing protected area network is shown to perform well under a changing climate, suggesting it should be maintained and expanded on rather than completely redrawn.

4.2 Introduction

Biodiversity is being lost at an unprecedented rate across the globe (Ceballos et al. 2017; Davidson et al. 2017), with the impacts of climate change likely to exacerbate these losses, as well as leading to a dramatic redistributing of species (Thomas et al. 2004a; Warren et al. 2011, 2018). In order to minimise species losses conservation management is required to protect those most vulnerable, but resources to achieve this are always limited and prioritising how they are best allocated is an ongoing concern for practitioners (Mace et al. 2000; Wilson et al. 2007a). Identifying which areas of a landscape will provide the most return on investment from conservation action is one of the key decisions in conservation management, with these decisions commonly informed using some form of systematic spatial prioritisation analysis (Wilson et al. 2007a; Kukkala & Moilanen 2013; Lehtomäki & Moilanen 2013).

There is strong evidence to suggest that spatial prioritisation is most effective when carried out across large spatial extents, ideally at a global scale to produce optimum results (Brooks et al. 2006; Moilanen & Arponen 2011; Montesino Pouzols et al. 2014). Despite this message of ‘think global, act local’ being proposed by the spatial prioritisation community, the practicalities of decision making being done within political boundaries means practitioners are often not basing planning decisions on this broader and more informative spatial scale (Halpern et al. 2006). As a result, approximately 90% of conservation spending is mostly concentrated within the more economically rich nations (James et al. 1999; Halpern et al. 2006) and not necessarily in the most biodiversity rich places in the global context. To help address this mismatch and with the aim of improving the effectiveness of spatial conservation planning, I aim to quantify the difference in effectiveness between spatial planning at the national scale against planning at a continental scale for all of Europe. I also attempt to produce a new way for conservation practitioners to benefit from the additional information of a full continental scale prioritisation in terms of incorporating the relative importance of species within their borders in the full European context by converting the results of the full prioritisation into a set of priority rankings for each country individually.

The key way in which priority areas identified by spatial prioritisation techniques are managed to ensure they actually produce benefits for biodiversity is by establishing them as protected areas. The importance of protected areas for biodiversity conservation is widely recognised (Butchart et al. 2010; Geldmann et al. 2013; Gray et al. 2016), with various targets and agreements between governments in place to ensure the levels of protection are maintained or even increased in the future (CBD 2010; Venter et al. 2014; Watson et al. 2014). There have been suggestions that the existing protected area network may become less effective under climate change (Araújo et al. 2004; Hannah et al. 2007; Hole et al. 2009), as species that currently occupy protected areas are forced to shift their distributions polewards (Hickling et al. 2006; Chen et al. 2011; Mason et al. 2015) leading to the need for them to find new suitable climate space outside of designated sites. Using the spatial prioritisations for the entirety of Europe I am able to test the performance of the existing protected network at present with known species distributions, as well as projected future performance using species distributions modelled under a range of potential climate scenarios.

Here, using the full European distributions of birds and butterflies at 50 x 50 km spatial scale, I present the results of a comparison of the effectiveness of a formal spatial prioritisation analysis, using the software package Zonation (Lehtomäki & Moilanen 2013), at a best practice continental scale compared with the national scale more commonly used by conservation practitioners and decision makers. I also test a novel approach based on using the information from the full-scale prioritisation and converting it into a format suitable for national level planning, which is more practical for use in making conservation decisions by smaller national entities. In addition, I examine the effectiveness of the existing European protected area network, both now and in the future under climate change, in order to address concerns about sites decreasing in importance as species distributions change over the course of the century.

4.3 Methods

4.3.1 Species Distribution Modelling

I produced species distribution models for both the current and projected future distributions of 395 birds and 380 butterfly species across Europe, based on 50 x 50km gridded atlas data (Hagemeijer & Blair 1997; Kudrna et al. 2011), using a Bayesian hierarchical, spatially explicit (Conditional Autoregressive) Generalised Additive Model, incorporating 4 bioclimatic variables and including a measure of observer effort. This approach allows me to separate climatic, spatial and random components determining the distribution of each species and to account for potential spatial autocorrelation in the distribution data (Beale et al. 2014).

The bioclimatic variables included in the model were: mean temperature of the coldest month (a measure of winter cold), coefficient of variation of mean temperature (a measure of seasonality), growing degree days above >5°C (a measure of growing season length) and soil water availability. Each of these variables has been shown to be an important predictor of both bird and butterfly distributions, through either direct physiological impacts on species or indirect effects on vegetation used by the species (Crick 2004; Araújo et al. 2005; Huntley et al. 2008; Heikkinen et al. 2010; Beale et al. 2014). To calculate the bioclimatic variables, monthly data for mean temperature, precipitation and cloud cover were required, in addition to soil available water content data. Current climate data was obtained from the CRU TS3.10 gridded dataset (Harris et al. 2014) and soil water data were obtained from the ISRIC-WISE global dataset of derived soil properties (Batjes 2005), with all of these data downloaded at 0.5° × 0.5° spatial resolution.

Projected future climate data for 3 Representative Concentration Pathways (RCP) were considered; RCP 2.6, RCP 4.5 and RCP 8.5, corresponding to 1.11, 1.5 and 2.11°C of warming on average across Europe (relative to the 1980-99 baseline), with models for each species were produced under each of these potential future climate trajectories. Climate variables based on each of the three RCP trajectories were obtained from the HadGEM2-ES model from the CMIP5 model set at 0.5° × 0.5° spatial resolution (Osborn 2009). Monthly values from these models were averaged over the time period 2070-2100, meaning the models represent end of century projections for species distributions, and the bioclimatic variables for the future scenarios calculated in the same way as for the current bioclimatic variables.

A measure of observer effort for each 50 x 50km grid cell was included in the species distribution models, which allows me to account for potential differences in sampling effort across geographical regions and between the different taxonomic groups. The observer effort measure was calculated as the ratio of the number of species observed within a given 50 x 50km cell relative to the number of species expected to occupy that same cell based on compositional similarity to a nearby neighbourhood of cells. This value of expected number of species per cell was calculated with the software FRESCALO (Hill 2012), using the ‘sparta’ package to implement the process within R (August et al. 2015). I considered the compositional similarity of cells based on the proportions of different habitats present within the cell, derived from the Corine Land Cover 2006 dataset.

Under future climate change, Europe is projected to experience climatic conditions beyond the extremes of conditions currently observed, leading to new novel climates occurring within the boundary I am using for my spatial prioritisation. As many of the species considered in the analysis occur outside of this boundary, it is highly likely that a large proportion of species may be able to persist under these conditions, even if they have not had to do so within Europe previously and distribution models based solely on European distribution data of species may overestimate the magnitude of potential shifts in species distributions.

To address this issue, I modelled species distributions at two spatial scales (where data was available to do so) - the entire Western Palearctic biogeographic region (30-75°N, -15-65°E) and Europe (35-72°N, -15-30°E). Distribution data for the Western Palearctic was obtained from species range polygons (BirdLife International & NatureServe 2015) rasterized to a 1 degree resolution. For the butterfly species, Western Palearctic distribution data from GBIF records and polygon data (Tshikolovets 2011) again rasterized to 1° × 1° spatial resolution.

Models were initially constructed using uninformative priors to describe the relationship between occurrence and climate at a broad spatial resolution (1 degree). A second model was subsequently fitted to the finer-scale (50 x 50 km) distribution data from Europe using informative priors generated from the Western Palearctic scale analysis. As a result, any strong climatic signal based on the Western Palearctic distribution would remain essentially unchanged when modelled using European data only, unless the climatic signal within the European distribution was markedly different. In cases where there was uncertainty in the estimation of species' responses at a Western Palearctic scale, then the finer scale model would be more heavily informed by outputs from the European component of the model. For species endemic to Europe, it was only possible to model at the finer spatial scale using uninformative priors, but as this describes the entire global range of the species this analysis is appropriate as any new climatic conditions experienced across Europe would be truly novel for those species.

4.3.2 Spatial Prioritisations

I performed a formal spatial prioritisation for the entirety of Europe for all bird and butterfly species I could generate species distribution models for. The prioritisation was carried out in the software package Zonation v4.0 (Lehtomäki & Moilanen 2013), using the modelled distributions of both birds and butterflies at 50 x 50 km resolution. Prioritisations were generated based on the current species distributions, as well as for each of the three future projected distributions under the different RCP climate trajectories used in the modelling. I used the core-area zonation (CAZ) analysis variant of zonation to produce priority area maps iteratively ranking each 50 x 50 km cell from lowest to highest priority for conservation, this variant of the prioritisation is more heavily focussed on conserving complementarity than species richness and means a location can receive a high priority value if even just one species has a relatively important occurrence there. Species were unweighted within the prioritisation, meaning they were all considered of equal importance when setting priority areas regardless of any known exacerbating factors or increased levels of threat from any source.

I carried out the spatial prioritisation based on two different boundary levels, at the full continental scale for Europe and for each nation within Europe just within their own borders. For the full continental scale analysis the full European distributions of each species were used in the prioritisation, generating priority maps for both taxonomic groups separately. For the national scale analysis, the full European distribution for each species was cropped to include just the extent of each country individually. The prioritisation process was then run separately for each country, considering only those species present within its borders and only the extent of those species ranges within the country. The results of each of these national scale priority maps were then rescaled to between 0 and 1 for each country and recombined to produce an overall prioritisation for Europe as a whole that could be compared directly with the full continental scale approach.

The key difference between the continental and national scale prioritisation is that with continental-scale rankings, top ranking cells may be concentrated in only a few countries and it is possible for a region to have no cells in the top fraction of importance for conservation. By contrast, in national level rankings and rescaling to the continental level, each country must have cells in all quantiles, providing local scale targets for conservation action in each country. This makes using the results of a continental scale prioritisation difficult to implement for two main reasons, firstly it would prove politically difficult to persuade a country with relatively low priority areas for conservation to pay for conservation management in other countries with higher priority areas (e.g. UK conservation budget used to pay for conservation management in the Alps), Secondly, there are numerous benefits to people having access to areas of high natural value, including improved health (Barton et al. 2009) and by focussing management on high priority areas in just a few countries we would lose these benefits in many places. It is also likely that some relatively poor countries would be asked to set aside almost all their land for conservation under a continental scale prioritisation and there is certainly some obligation in allowing development in these biodiversity rich areas.

To attempt to address the difficulties of implementing the results of the full continental approach, whilst still retaining the additional information provided by using the full species distribution, I rescale the full continental prioritisation results within each country's borders. This rescaled continental prioritisation is achieved by cropping each country out of the full prioritisation and converting the rankings of the cells to between 0 and 1, whilst retaining the order of importance from the full European scale assessment. This process results in an output where each nation has the same proportion of landscape as high priority areas as every other nation, albeit in potentially different locations to either the national or full continental scale prioritisations. The rescaled prioritisation, addresses one of the main limitations of the full continental approach in leaving some areas under represented in terms of importance.

Some countries within Europe were too small (< 20 50 x 50 km cells) to run the spatial prioritisation at the national scale, so were omitted from the analysis. The same countries were also removed from both the continental and rescaled continental approaches to ensure all comparisons of efficiency of the different scales of prioritisation were the same, although the distributions of species within these countries were included in the prioritisation originally.

4.3.4 Effectiveness of prioritisation

To compare the differences in efficiency of the three different spatial scales of prioritisation I calculated the proportion of each species' distribution that was protected at a given level of the total landscape under protection, from 0 to 100% of European terrestrial land, and averaged the results for each of the three prioritisation scenarios considered. As well as considering the overall pattern across the entire landscape I also consider the differences at a set threshold of landscape under protection, using the Aichi target of 17% of terrestrial land protected (CBD 2010).

Another way I considered the efficiency differences is to evaluate how much extra land would be required for conservation to achieve the same level of average value of species distributions protected, comparing the ‘best’ 17% of the landscape based on the full continental approach against each of the other prioritisation approaches.

4.3.4 Protected Areas

To examine how well the existing protected area network in Europe performs compared with the priority areas identified by the spatial prioritisation analysis, I examine the overlap between the two datasets. Data for the locations of protected areas was obtained from ‘Protected Planet’ (UNEP-WCMC & IUCN 2016), with all terrestrial sites classified as IUCN categories I-IV considered as part of the protected area network in Europe given their importance for species conservation. I did not consider IUCN category V and VI sites in the protected area network, due to their focus on landscape rather than species level conservation and less strict regulation of activities within the sites.

The protected area sites were rasterized to the same 50 x 50 km grid used in the spatial prioritisation, with the total coverage of the cell by protected area sites calculated, generating a range of values between 0 and 100% coverage. The rasterization and calculations were both completed in R v. 3.4.2 (R Core Team 2016) using the ‘raster’ package (Hijmans 2016).

I compared the distribution of the existing sites within the entire terrestrial protected area network in Europe against the full continental scale spatial prioritisations for each of the three projected futures under climate change, to examine how well the existing protected area network overlaps with the projected priority areas.

4.3.5 Statistical Analysis

To examine the agreement between the three different approaches to spatial prioritisation for Europe, as well as to consider the overlap between the priority areas and existing protected area network I used Spearman's rank correlations. To examine the differences in efficiency of each of the three spatial prioritisation approaches at the 17% land protected threshold I used the non-parametric Wilcoxon Signed Rank test to compare the differences in proportion of total European distribution for each species pairwise for each combination of the approaches.

All statistical analysis and calculations were performed in R v.3.4.2 (R Core Team 2016).

4.4 Results

4.4.1 Spatial similarities and differences between approaches

The spatial prioritisations for Europe based on the three different spatial scales each produce different patterns of where the most important cells for conservation are located (Figure 4.1). The full continental scale prioritisation produces the most ‘joined-up’ network of highest priority areas, with northern Fennoscandia, south eastern Europe and Iberia particularly important for both birds and butterflies. The priority maps show a similar pattern of areas of importance for both birds and butterflies, with a moderate positive correlation between the taxonomic groups ($r_s = 0.43$, $p < 0.001$). There are, however, several regions with relatively few high priority cells for either taxonomic group, including central Europe and southern Scandinavia as well as the UK and Ireland for butterflies.

The national level prioritisation produces a very different pattern of highest priority areas compared with the full continental scale approach, with only a relatively weak correlation between the two approaches for either birds or butterflies (Spearman’s rank correlation - birds: $r_s = 0.16$, $p <0.001$, butterflies: $r_s = 0.17$, $p < 0.001$). The national scale prioritisation produces a map where the highest priority areas for conservation are much less contiguous, with the most important cells scattered more evenly across the continent and fewer large patches of the most important areas in a single region as seen in the full continental scale analysis.

The rescaled continental scale produces a priority map approximately intermediate between the full and national scale results, although more similar to the continental analysis overall. There is much stronger correlation between the rescaled and full continental prioritisations (birds: $r_s = 0.72$, $p <0.001$, butterflies: $r_s = 0.68$, $p < 0.001$) than there is for the rescaled with the national only approach (birds: $r_s = 0.22$, $p <0.001$, butterflies: $r_s = 0.20$, $p < 0.001$).

I find weak overlap between the highest priority areas in the spatial prioritisation based on current species distributions and the cells with the highest percentage coverage of protected areas for either taxonomic group (Figure S4.1, birds: $r_s = 0.008$, $p = 0.73$, butterflies: $r_s = 0.092$, $p < 0.001$). The national only prioritisation shows stronger overall agreement with protected area coverage for the birds and similar agreement for the butterflies compared with the full continental approach (Figure S4.1, birds: $r_s = 0.035$, $p = 0.12$, butterflies: $r_s = 0.077$, $p < 0.001$), although as protected areas are normally designated at the national level stronger overlap between the priority areas and the coverage of protected areas might have been expected at this scale. The continental rescaled approach has the greatest overlap of priority areas and protected area coverage for both taxonomic groups compared with the other approaches, particularly for the butterfly species (Figure S4.1, birds: $r_s = 0.045$, $p = 0.043$, butterflies: $r_s = 0.23$, $p < 0.001$).

Considering just the top 25% highest priority cells based on the current species distributions, for birds almost half (249/510, 48%) have less than 1% protected area coverage, with a slightly higher number reaching that amount of coverage for butterflies (207/510, 41%), suggesting a large proportion of the most important cells for birds and butterflies remain inadequately protected. Although I identify little overlap with the highest priority cells and existing protected area sites, I did find stronger agreement that the cells with the highest coverage of protected areas are also high priority in the spatial prioritisation if I consider just the cells with ≥17% protected area coverage (birds: $r_s = 0.39$, $p < 0.001$, butterflies: $r_s = 0.27$, $p < 0.001$).

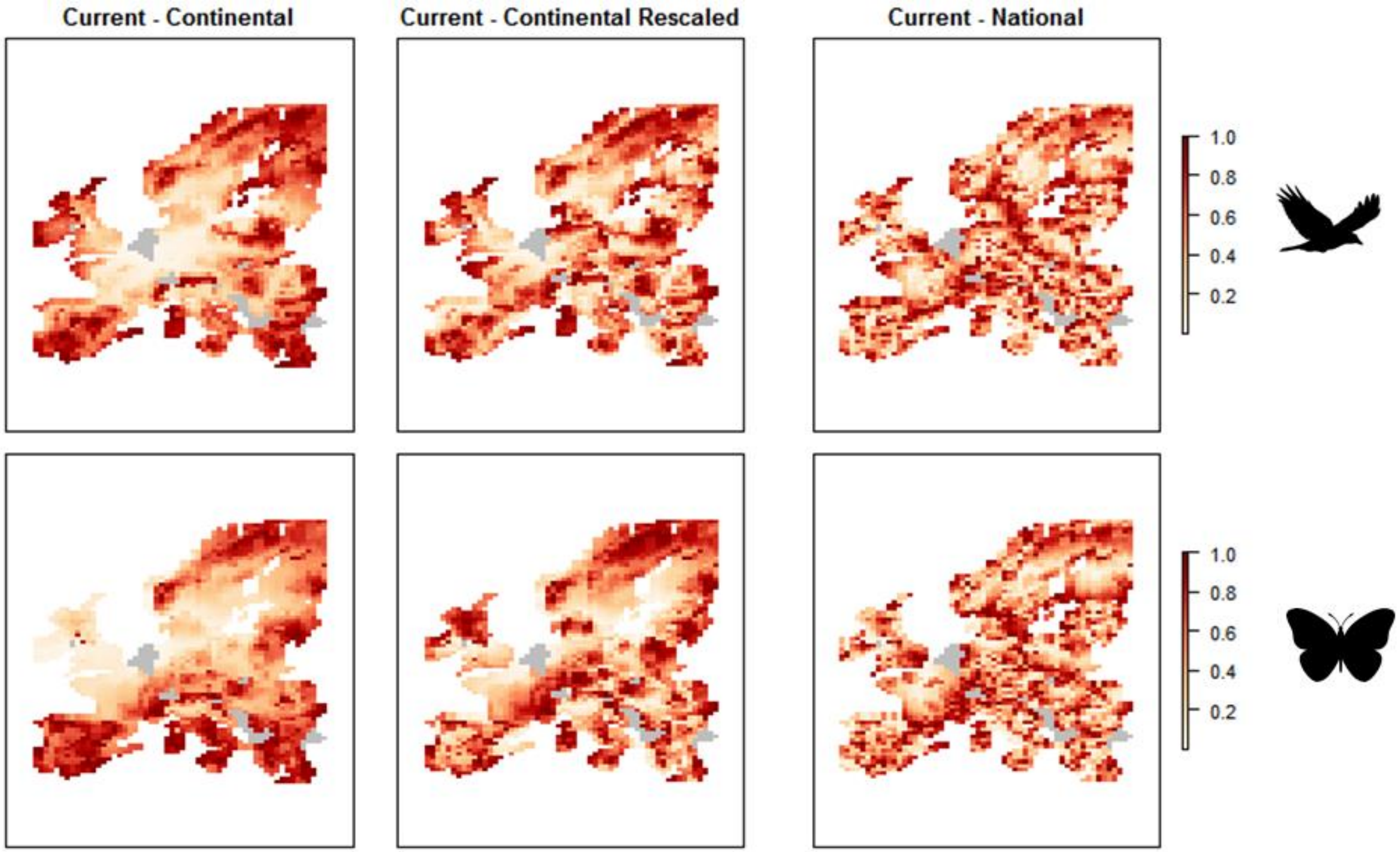


Figure 4.1. Priority area maps for Europe based on each of the three prioritisation approaches used. The areas of least importance are shown in white with the most important areas in dark purple. Areas in grey are those I was unable to run the national level prioritisation at 50 x 50 km resolution, so have been excluded from all three prioritisation approaches. Priority maps for birds are on the top row, with butterflies on the bottom row.

4.4.2 Species representation and the Aichi targets

Although I identify similarities between the full and rescaled continental prioritisations, with less overlap with the national scale approach in both cases, this does not give any indication of which of the approaches would provide the most benefit in terms of protecting species across the European landscape. The full continental scale analysis protects a greater proportion of species distributions on average across all levels of landscape protection, for both birds and butterflies, than either of the other prioritisation scenarios (Figure 4.2). Indeed, the national only approach is only marginally better than the 1:1 ratio that would be expected by prioritising randomly, suggesting it may not be a particularly suitable approach to utilise. At the 17% Aichi target threshold the full continental scale approach is on average 23% and 36% more effective than the national scale approach, for birds and butterflies respectively.

The full continental approach is also more effective than the rescaled continental approach, but the difference is less pronounced than with the national only approach. Again considering the 17% Aichi target threshold the full approach is on average 10% more effective for birds and 24% more effective for butterflies, although the difference in effectiveness does continue to increase as the percentage of landscape protected increases, up to about 80% of the total area of Europe. The rescaled continental approach also out performs the national only approach by 15% for the birds and 17% for butterflies, again at the 17% Aichi target threshold. All three prioritisation approaches perform well for butterflies, while for birds the continental and rescaled continental approaches are not as effective but still perform well.

Considering the amount of land required to achieve the same level of species ranges protected at the 17% Aichi target under the full continental approach, for birds 22% of the landscape would be required to achieve the same conservation value using the national-scale approach, but just 18% for the continental rescaled. For butterflies the national only approach would require a large increase in landscape protection to 28% and an increase to 23% under the continental rescaled approach.

The averaged value across all species may hide some variation in the performance of the different approaches, so I also examine the differences on an individual species by species basis (Figure 4.3). For both taxonomic groups the full continental scale prioritisation still performs best for the majority of species, with 476/775 (61%) species having a greater fraction of their distribution protected compared with the national approach and 440/775 (57%) species better protected than with the rescaled approach at the 17% landscape protection threshold. The magnitude of these differences are statistically significant, with the full continental scale prioritisation protecting higher proportions of species distributions for both taxonomic groups (Table 4.1, histograms of differences shown in Figure S4.1). The rescaled continental approach also works more effectively than the national scale approach, providing higher levels of protection for 421/775 (54%), again statistically significant (Table 4.1, histograms of differences shown in Figure S4.2).

These overall average performance differences are significant, but relatively modest in magnitude. However, conservation planners are more likely to be interested in maintaining populations of rare species; the analyses show that, for butterflies in particular, it is predominantly small-range species that receive additional benefit from a continental prioritisation (Figure 4.4). Recalculating the previous values for the 50% of species with the smallest European range areas (195 birds and 188 butterflies), I find that 286/383 (74%) of these small range species are better protected by the full continental scale prioritisation compared with the national approach and 247/383 (65%). The rescaled continental approach again works more effectively than the national scale approach for range limited species, providing higher levels of protection for 266/383 (69%), with all these differences statistically significant (Table 4.1).

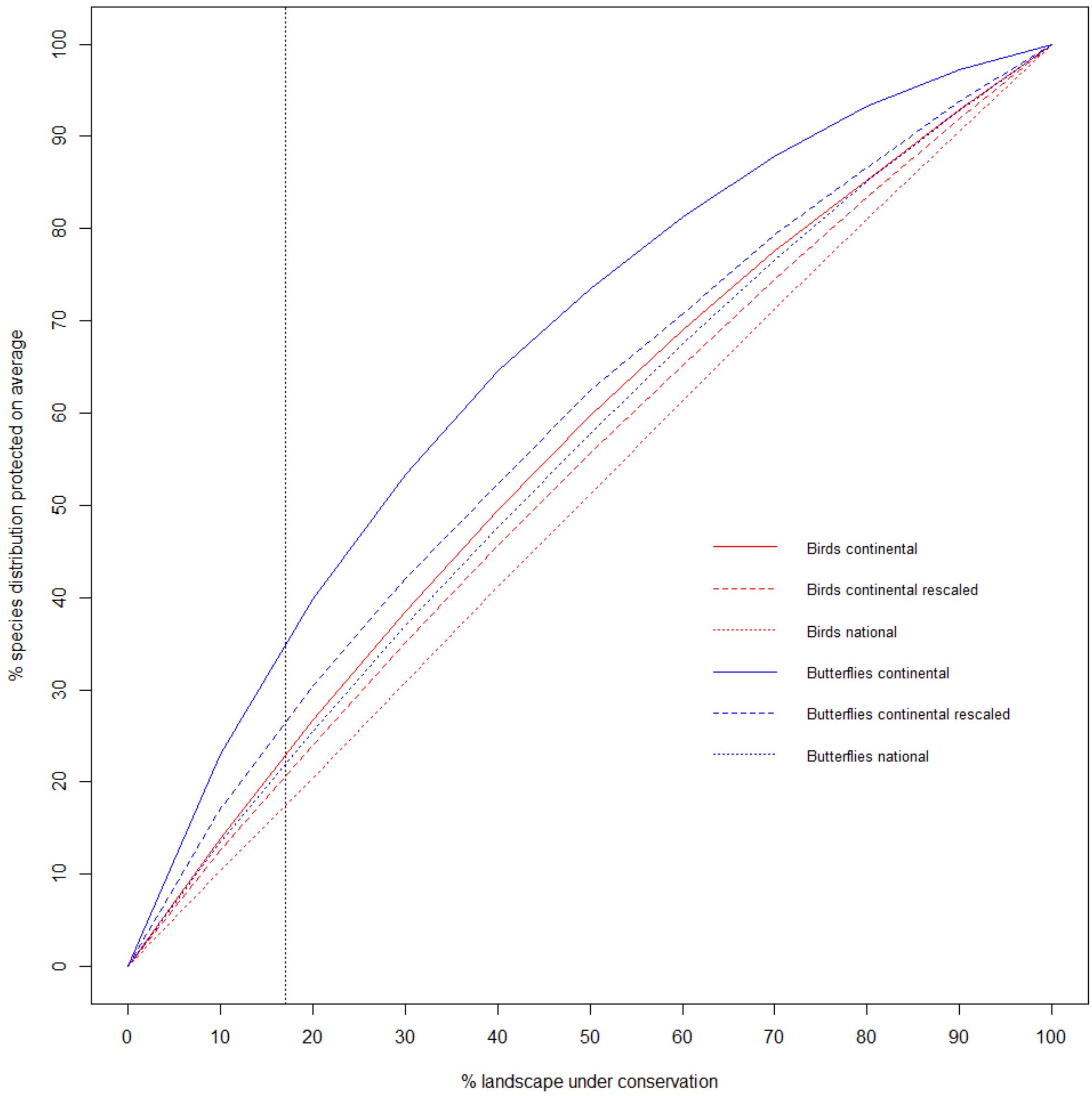


Figure 4.2. Accumulation curves showing the mean percentage of all species current distributions protected at varying levels of total landscape protection, ranging from none to the entire landscape protected under each of the three prioritisation scenarios. Solid lines represent the full continental scale prioritisation, the dashed lines the rescaled continental analysis and the dotted line the national only prioritisation. Red lines represent the prioritisations for birds and blue lines the prioritisations for butterflies. The vertical dotted line represents the 17% Aichi target threshold used for comparisons within the main text.

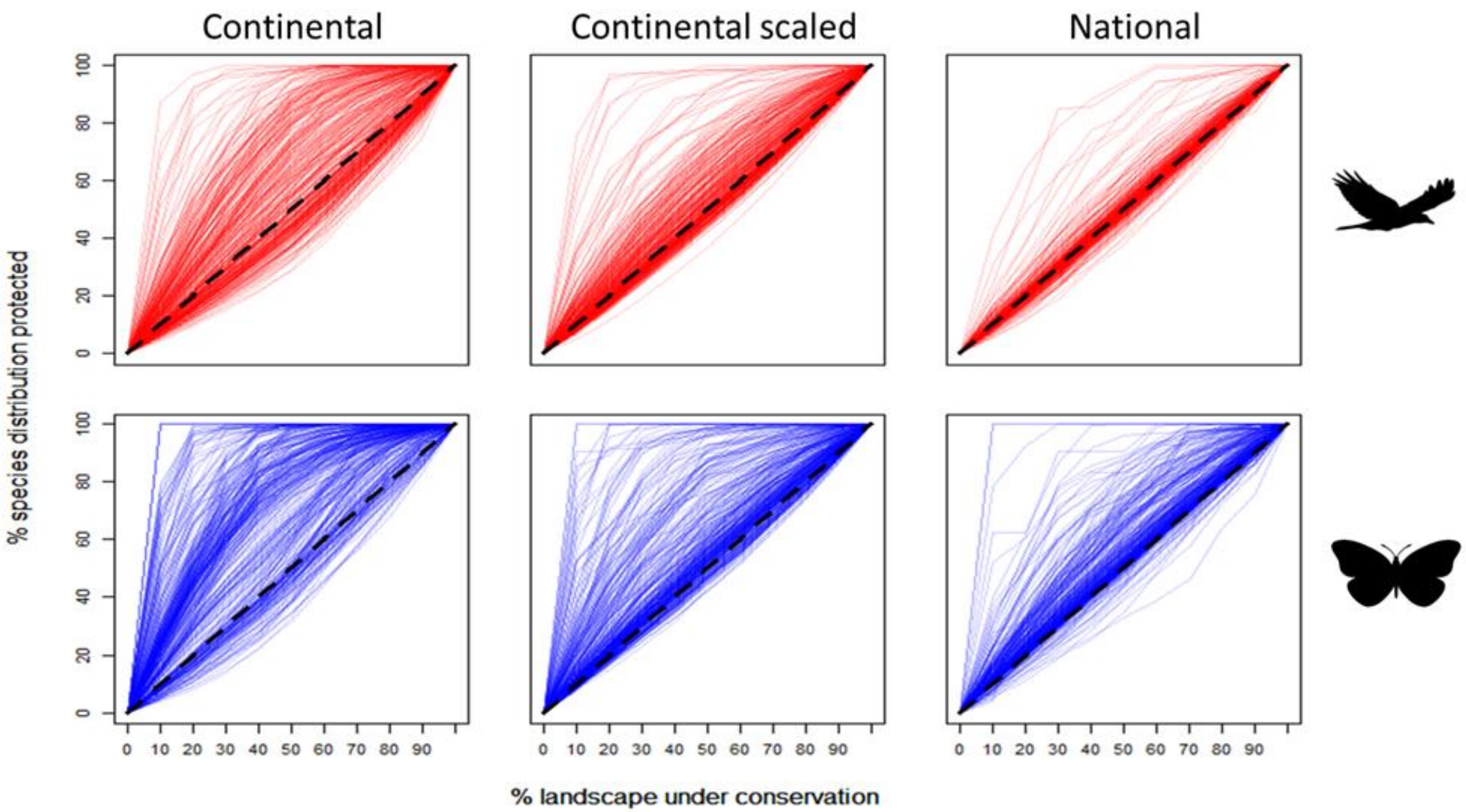


Figure 4.3. Accumulation curves for each individual species included within the spatial prioritisations, showing what percentage of their current distribution would be protected at varying levels of total landscape protection, ranging from none to the entire landscape protected. The dotted black line represents the 1:1 ratio of landscape protection and species range protection, effectively the expectation if protecting areas randomly. Each of the three columns represents a single one of the three approaches to spatial prioritisation for Europe, with birds on the top row (red lines) and butterflies on the bottom row (blue lines).

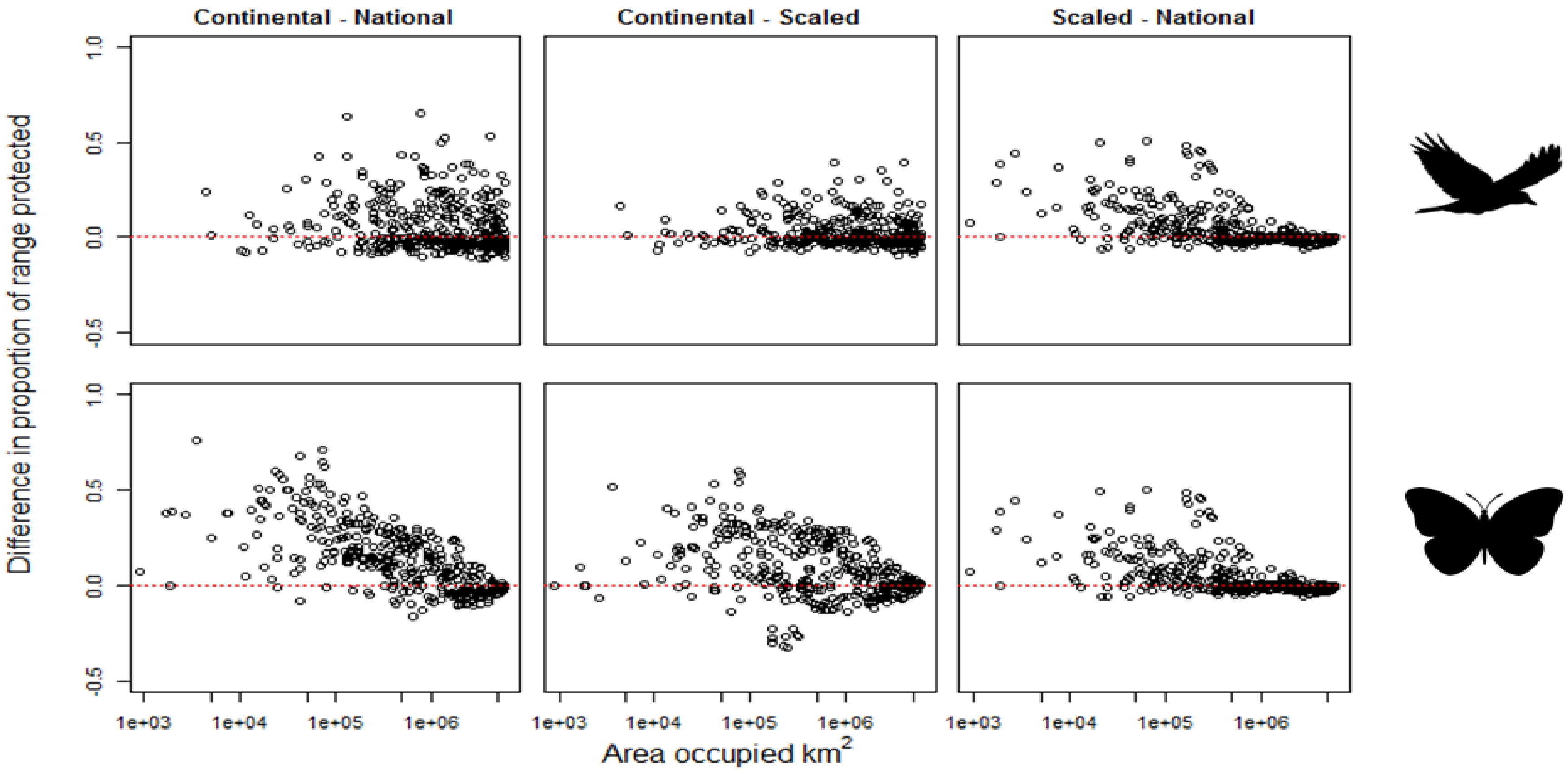


Figure 4.4. Differences in proportion of range protected for comparisons of each of the three prioritisation approaches at 17% of total landscape protection, against the current range size of each species. A positive difference shows the prioritisation approach listed first performed better for a species than the approach listed second in the comparison. Results for birds are on the top row and butterflies on the bottom.

Table 4.1: Wilcoxon signed-rank test results for pairwise comparisons of proportion of species distributions protected under each of the three prioritisation approaches. All significant results are in the same direction, with the first prioritisation approach listed in the comparison having the higher mean rank value, indicating a larger fraction of a species distribution is protected under that prioritisation approach.

Prioritisation Approach	**Birds**	**Butterflies**
All species		
Continental vs National	V = 52493, $p < 0.001$	V = 61934, $p < 0.001$
Continental vs Rescaled	V = 44950, $p < 0.001$	V = 54429, $p < 0.001$
Rescaled vs National	V = 23620, $p < 0.001$	V = 21955, $p < 0.001$
Small range species		
Continental vs National	V = 14567, $p < 0.001$	V = 17241, $p < 0.001$
Continental vs Rescaled	V = 12596, $p < 0.001$	V = 14820, $p < 0.001$
Rescaled vs National	V = 14434, $p < 0.001$	V = 15864, $p < 0.001$

4.4.3 Similarities of prioritisation approaches under climate change

Carrying out equivalent analysis as to those as above demonstrates broad conclusions about the efficiency differences for the three prioritisation approaches hold for each of the three future climate scenarios considered. Under all climate change scenarios and for both taxonomic groups, the full continental scale prioritisation remains more effective at protecting species that either the rescaled or national approaches (Table 4.2). The size of the differences between the approaches does reduce as the magnitude of climate change included in the model increases, with very small differences between the full and rescaled approaches under the highest climate change scenario. However, even under the high emissions climate change scenario the full continental prioritisation still provides a close to 20% improvement over the national only approach for both birds and butterflies.

When examining the differences on an individual species by species basis for both taxonomic groups the full continental scale prioritisation still performs consistently better for the majority of species when compared to the national only approach, with the difference in performance increasing when considering only the smallest range species (Table 4.3). The same pattern is found when comparing the rescaled continental with the national only approach, with the rescaled consistently performing better for higher numbers of species than the national only. The full continental scale prioritisation consistently protects more butterfly species than the rescaled approach does, but under some climate scenarios the rescaled approach actually protects greater numbers of species than the full continental scale approach.

Table 4.2. Percentage difference in proportion of species distributions protected on average at 17% total landscape protection, for present distributions and distributions under each of the three climate change scenarios considered. All differences are positive indicating a larger fraction of species distributions are protected on average under the first prioritisation approach listed in the comparison.

	Model Scenario							
Prioritisation Approach	**Current**		**RCP 2.6**		**RCP 4.5**		**RCP 8.5**	
	Birds	**Butterflies**	**Birds**	**Butterflies**	**Birds**	**Butterflies**	**Birds**	**Butterflies**
Continental vs National	+23%	+36%	+18%	+24%	+18%	+22%	+18%	+20%
Continental vs Rescaled	+10%	+24%	+5%	+17%	+5%	+14%	+3%	+6%
Rescaled vs National	+15%	+17%	+14%	+8%	+15%	+8%	+15%	+14%

Table 4.3. Proportion of species with a greater proportion of their distributions protected at 17% total landscape protection under the first prioritisation approach listed in the comparison, for present distributions and distributions under each of the three climate change scenarios considered.

Prioritisation Approach		Current		RCP 2.6		RCP 4.5		RCP 8.5	
		Birds	**Butterflies**	**Birds**	**Butterflies**	**Birds**	**Butterflies**	**Birds**	**Butterflies**
Continental vs National	***All species***	0.53	0.72	0.55	0.66	0.56	0.70	0.53	0.70
	Small range species	0.58	0.91	0.58	0.82	0.60	0.90	0.54	0.75
Continental vs Rescaled	***All species***	0.49	0.66	0.48	0.60	0.51	0.70	0.47	0.59
	Small range species	0.53	0.76	0.50	0.77	0.54	0.85	0.48	0.75
Rescaled vs National	***All species***	0.53	0.57	0.56	0.64	0.51	0.59	0.60	0.79
	Small range species	0.58	0.80	0.56	0.64	0.54	0.69	0.62	0.76

4.4.4 Existing conservation provision and climate change impacts

The overlap between protected area network and priority areas increases under each of the climate change scenarios considered for the birds (r_s = 0.06 - 0.12, all $p < 0.001$), showing that the performance of the existing protected area network is projected to improve, not worsen, under climate change for this taxonomic group. For the prioritisations involving butterflies, there is little difference in overlap between the prioritisations based on current and future low/medium species distributions and the existing protected area network (r_s = 0.052 - 0.074, $p < 0.001$) but the prioritisation based on the species distributions under the high climate change scenario does show increased overlap the same as for the birds ($r_s = 0.17$, $p < 0.001$).

If I again consider just the top 25% highest priority cells based on modelled distributions under the three future climate scenarios, I find a decrease in the number of cells with less than 1% protected area coverage than based on current distributions. These numbers decrease under the future prioritisations for birds under all scenarios (low: 45%, medium: 43%, high: 41%) and under the highest climate scenario for butterflies (low: 41%, medium: 41%, high: 36%), which is consistent with finding that overlap between the current protected area network and the spatial prioritisations increases marginally under climate change.

4.5 Discussion

It is clear that the scale at which spatial prioritisation is performed for a given landscape can produce markedly different results (Figure 4.1). In terms of providing the maximum benefit for conservation, the full continental scale analysis consistently performs best out of the three different approaches that were considered over all levels of landscape protected, for both taxonomic groups, but particularly for butterflies (Figure 4.2). The lower efficiency for birds arises because they have larger average range sizes, and thereby lower levels of local endemism in particular parts of Europe, permitting a greater proportion of the distributions of small range butterfly species to be encompassed within a relatively small fraction of the land area. The full continental approach is particularly beneficial for species that have small distributions across the entirety of Europe, as large fractions of their distribution are quickly protected in the prioritisation (Figure 4.3) leading to many species with a >20% difference in the amount of their range protected versus the national approach (Figure S4.1).

When prioritising the landscape for each country separately, species that are widely distributed across Europe but have only a small fraction of their range within a particular country can repeatedly ranked as high priority in multiple nations, despite them already being accounted for in numerous locations already. This can even lead to a situation where species truly endemic to a country are prioritised behind species that are widely distributed, but only occupy a few cells in that country and in terms of maximising resources to protect biodiversity this is undesirable.

Despite the increased efficiency of the full continental scale approach to spatial planning, it does have the inherent limitation that some countries within the prioritisation area will be under-represented in terms of having high priority areas in which to target conservation action. As each country currently manages their own conservation resources and planning, using a completely joined up approach to conservation planning will remain an impossibility even if the evidence suggests it would provide the greatest return on total investment. The results of the rescaled continental approach do compare favourably to the national only approach, providing increased protection of species distributions for the same total of landscape protected. Species do not respect political boundaries, and to act as if they do causes a loss of important information that can be incorporated into prioritisation analyses. In practical usability terms it should be straightforward for conservation practitioners to utilise the information about full species distributions into their spatial prioritisations using the rescaling approach and doing so will improve their conservation outcomes

Even though both spatial prioritisation approaches making use of the continental scale species distribution data offer superior performance than the national only approach, there are still some intangible aspects of prioritising species conservation not captured by pure spatial prioritization. For instance, popular charismatic species may not be protected within the borders of countries where the demand to see them is high under a pure spatial prioritisation, which may have impacts for industries such as ecotourism (Maciejewski & Kerley 2014). Incorporating this kind of information into a spatial prioritisation is difficult, and in many cases would be completely subjective, but could be achieved to some extent by weighting key species more heavily in the prioritisation process by practitioners or decision makers within each country. If implemented fully, the continental scale European spatial prioritisation would also have the potential to increase the damage from catastrophic events, both natural and man-made, if species are only protected in a single region and the population is heavily reduced (Liao et al. 2015).

When considering the effectiveness of the existing protected areas based on the spatial prioritisation, the results suggest that the current network may be missing some important priority areas for birds and butterflies, as evidenced by the poor correlation between the full continental scale spatial prioritisation and the percentage cover of protected area for each cell (Figure 4.4). This highlights the need to further expand the protected area network in Europe if we are to ensure some of the most important areas for species conservation are given adequate attention. As protected areas are designated for species other than birds and butterflies, that may explain some of the poor agreement with priority areas. However, birds and butterflies are heavily featured in target species lists so should be representative of protected area network performance. The high level of overlap between birds and butterfly prioritisations also suggests that the priority areas for these taxonomic groups are likely to be important for other species from a range of different taxonomic groups.

It has been suggested that some protected areas could, or perhaps should, be downgraded, particularly if they are no longer meeting targets for the species they were originally designated for (Cliquet et al. 2009; Fuller et al. 2010; Pack et al. 2016). However, the results suggest that the existing protected area network will continue to be important for some of the highest priority cells, even under the largest projected magnitude of climate change I considered, as evidenced by the high overlap of the cells with highest levels of existing protection and those ranked highest in the spatial prioritisations. For some sites this will be due to the sites acting as refugia for the species they were originally designated for, although for other sites it may be for entirely different species arriving in the future due to the impacts of climate change causing shifting distributions. Existing protected sites have been shown to be of great importance for colonising species and are disproportionately occupied by species expanding their ranges under climate change (Thomas et al. 2012; Beale et al. 2013; Gillingham et al. 2015; Thomas & Gillingham 2015), which could explain the strong overlap of the existing protected area network and the future spatial prioritisations in this analysis.

Consideration of where to target the expansion of the protected area network to increase coverage of the high priority areas that are being missed, both now and in the future, in addition to maintaining existing sites in a balanced way for new arrivals as well as existing species is needed to generate better conservation outcomes. Selecting protected areas based on their likely resilience to or expected benefits from future climate change has already started to be considered by conservation practitioners (Gilbert et al. 2010) and the results suggest it should continue to be an important consideration, despite concerns around the possibility of priority species shifting their distributions outside of designated sites (Araújo et al. 2004; Hole et al. 2009).

To conclude, incorporating the relative importance of species at the widest possible spatial scale can significantly improve the effectiveness of spatial prioritisations and remains the best practice approach to these planning problems. However, if planning can only be implemented at a local scale than rescaling the results of a broader scale analysis to just the region of interest will still improve the effectiveness of the prioritisation compared to acting with just the local scale information. The existing protected area network in Europe is likely to remain fit for purpose as species are forced to shift their distributions under climate change, with some sites even increasing in importance relative to the present day. Despite this potential improvement, expansion of the network and creation of new designated sites will be required to ensure some key priority areas are not left without adequate protection for the species within them.

Chapter 5 General Discussion

5.1 Summary of thesis findings

In this thesis I have used large scale predictive modelling to examine the risks and opportunities climate change poses to European biodiversity. In **Chapter 2**, I examined a range of commonly used climate change vulnerability assessment methodologies to identify if they reached a consensus on which species are most likely to be threatened by climate change and validated to see if any accurately predicted declines under recent climate change. When comparing the results of the 12 different climate change vulnerability assessments considered, I found poor agreement between them when assigning the same species to risk categories. This pattern held for both the small sample of real exemplar species and the larger sample of simulated species trait sets. Using the simulated species data, I demonstrate that there is much stronger agreement between climate change vulnerability assessments using the same fundamental approach (trait, trend or hybrid), with very poor agreement between the different approach types.

To validate the performance of each of the 12 climate change vulnerability assessments, I used historic species data to perform the assessments for British birds and butterflies and compared the results to recent observed changes in population and distribution for each species. These comparisons demonstrated relatively poor performance from many of the assessments, with only two trend-based approaches showing significant predictive ability. Some assessments performed worse than random at predicting which species would decline under climate change, while the majority showed no significant trends at all for either population or distribution changes. The results of both the comparisons and validation of the assessments demonstrate that the different approaches should not be used interchangeably and based on the existing assessments available approaches that are trend-based should be preferred due to the superior performance of this type of approach in the validation.

In **Chapter 3**, I carried out a comprehensive climate change vulnerability assessment for European birds and butterflies was, using the best performing methodology identified in Chapter 2. A total of 395 birds and 380 butterflies were assessed, with future distributions modelled using three potential future climate change scenarios for 2080-2100 ranging from low to high magnitude of climatic change. I found different overall patterns of risk under climate change for the different taxonomic groups, for birds' similar numbers of species were assigned to both risk and opportunity categories, even under the climate scenario with the largest magnitude of projected change compared to the present day. A much higher proportion of the butterfly species assessed were identified as being at high risk from climate change, even under the lowest climate change scenario considered, with very few species showing limited impacts of changing conditions. Comparisons of climate risk scores against the existing IUCN Red List status of each species identified up to 253 species not of current conservation concern that are likely to require conservation intervention before the end of the century. The comparisons also highlighted that for the majority of currently threatened European birds and butterfly species climate change will be an additional threat to those already driving declines in their populations or distributions.

A spatial prioritisation for Europe under climate change was also carried out for both taxonomic groups, which demonstrated a general pattern of increasing importance of the north west Europe, with more dramatic shifts as the magnitude of climate change increased. Areas of the continent were also identified as being of high conservation importance both now and in the future under all climate change scenarios, particularly the Alps, southern Spain and northern Fennoscandia.

In **Chapter 4,** I examined the impact of the scale at which spatial prioritisation and conservation planning is performed at can have on the overall effectiveness of the process. The results of spatial prioritisation for the same total landscape area but using three different spatial scales (continental, continental rescaled and national) were compared to establish which approach provided the most effective approach to prioritise across the European landscape. At all levels of landscape protection the full continental scale approach protected a greater proportion of species distributions on average than either of the other approaches. This was partly driven by the full continental scale approach performing particularly well for range limited species, with the highest priority areas quickly capturing large proportions of their distributions with relatively little total area protected across the landscape. As these range limited, rare species are likely to be the species considered to be most valued by conservation practitioners, the improved performance of the continental prioritisation in protecting them should merit serious consideration when planning conservation management options.

Comparisons of the highest priority areas identified in the spatial prioritisation with the existing protected are network found relatively poor agreement for current species distributions, but under climate change the effectiveness of the protected area network is projected to increase. This would indicate that suggestions that the protected area network is likely to become unsuitable under climate change are unfounded, and that the existing network should be maintained and expanded upon to incorporate some of the highest priority areas not currently covered by protected sites.

All of the data chapters indicate that there will be widespread impacts of climate change on biodiversity in Europe, both positive and negative, for a range of species. The results of the spatial prioritisation analyses in both Chapters 3 and 4 highlight that there will be changes in which locations are most important for conservation and that we need to start considering these impacts if we are to maximise the value of conservation action for protecting biodiversity across the continent.

In the rest of this chapter I will consider the implications climate change has for planning biodiversity conservation into the future. I will also examine some of the limitations and uncertainty associated with how we currently attempt to incorporate these climate change impacts into the existing planning process, and consider if our current focus on single species conservation is justified. There will also be some discussion of the limitations of the work in this thesis and suggestions for further work and improvements around the topic of planning conservation management in the future incorporating the threats posed by climate change.

5.2 Biodiversity conservation in a changing climate

Global efforts towards climate change mitigation are focussed on limiting warming to well below a 2°C increase relative to pre industrial baseline, with ambitions from the Paris Agreement also targeting a limit of 1.5°C (UNFCC 2015). However, our current global emissions trajectory suggests we are on course to exceed even the RCP 8.5 scenario (considered as the high climate change scenario in Chapters 3 and 4), with limiting warming to 2°C looking increasingly unlikely (Sanford et al. 2014) and a high chance that we are already committed to levels of global warming that will exceed 1.5°C by the end of the century (Huntingford & Mercado 2016). It is also possible that the required level of land-use change for mitigation to achieve the limit of 1.5°C of warming could actually result in net carbon losses leading to further warming unless mitigation measures are carefully planned and implemented (Harper et al. 2018).

Even if global efforts to mitigate emissions do achieve the Paris agreement targets to limit warming to 2°C, the results of my climate change vulnerability assessment (Chapter 3) would suggest that even under the lowest magnitude climate change scenario considered there will still be large impacts of climate change on European biodiversity in terms of high numbers of species being at increased risk of extinction. Other studies have also found that even 2°C of warming will lead to dramatic losses of biodiversity, and while limiting change to 1.5°C will reduce the impact on biodiversity (Warren et al. 2018), we will still experience a very different natural world if emissions were to be stopped today.

In the face of the clear threat climate change poses to biodiversity globally, conservation goals or baselines need to be clearly defined to ensure conservationists and society more generally are working towards to same objective (Bull et al. 2014). Current conservation planning is generally a mixture of attempting to maintain the species we have at present in the locations they are currently found in, along with some efforts at using rewilding to return ecosystems and communities of species to some arbitrary past state (Navarro & Pereira 2015), but these conservation baselines are often poorly defined, prone to gradual shifting over time and evaluation of interventions to maintain them are often poor or not done at all (Papworth et al. 2009; Bull et al. 2014). It may be required for conservationists to instead accept that many species will have to move and community composition will alter under climate change, attempting to maintain historic species distributions is likely to prove futile and may come at the expense of ensuring new colonisers can establish in different regions.

It will be a major challenge for NGOs and governments to accept that climate change will cause large shifts in species distributions and likely require substantial changes to existing priorities, particularly with the current focus more on mitigating or reducing the level of change we will experience, rather than on preparing and planning for adaptation to the new conditions we will experience (Capela Lourenço et al. 2018). This is partly due to the fact that any future conservation planning attempting to incorporate projected future climate change is inherently uncertain, often leaving decision makers unclear on what the exact impacts will be on biodiversity and making it difficult to reach consensus on what to actually do about it. A better understanding and communication of what the major sources of uncertainty are, as well as how they can begin to be addressed, is needed to help those planning future conservation action.

5.3 Uncertainty in biodiversity conservation under climate change

There is clear evidence that climate change has and will continue to have dramatic impacts on biodiversity around the world (Araújo & Rahbek 2006; Foden et al. 2008; Urban 2015; Scheffers et al. 2016, Chapter 3), and action is needed to limit the negative impacts on species. However, any research or decision making around the potential impacts of future climate change on biodiversity is inherently difficult, due to the wide range of unknowns and uncertainties surrounding the issue (Lempert et al. 2004). Addressing this issue of uncertainty is crucial to ensure any action taken to attempt to limit the negative impacts of climate change on biodiversity are not wasted opportunities, or at worst actively harmful in leading conservation management and spending away from truly threatened species or locations (Beale & Lennon 2012).

One major source of uncertainty in prioritising species conservation for the future is from the climate change vulnerability assessment methodologies themselves, with little consistency between methods and poor performance at predicting risk from many approaches, as evidenced in Chapter 2 of this thesis. Practitioner and policy maker confidence in the results of climate change vulnerability assessments is of crucial importance to ensuring that there is uptake of results and that they are actually used to inform conservation management, without reducing some of the uncertainty associated with the vulnerability assessment process it is unlikely there will be widespread use of the outputs that are generated.

There is a clear need for further validation of existing climate change vulnerability assessments if they are to be used in the decision making process, the analysis in Chapter 2 is one of the first attempts to test framework performance, even though validation is crucial to demonstrating that methods can actually work and be of practical value. Despite the poor overall performance of many of the methods demonstrated in Chapter 2, new assessments are consistently appearing in the literature, either presenting or applying existing methods to different sets of species or regions, with little regard for how well they actually perform at predicting risk (Meng et al. 2016; Culp et al. 2017; Rempel & Hornseth 2017). Validation of new methodologies needs to become standard practice, and further validation of existing methods using a wider range of species and over longer time periods as data becomes available is recommended to ensure continued confidence in any approach used in the conservation decision making process.

The reliance on trait data in the vulnerability assessment process is another source of substantial uncertainty, the data can often be difficult to obtain, there is often no guidance on how to deal with missing data in the assessment process and best guess ‘expert opinion’ is often used when data is not available. Fundamentally it is through traits that species interact with their environment so they should be useful predictors of risk and there is good theoretical support that trait data can predict the impact of climate change on species distributions (Angert et al. 2011; Buckley & Kingsolver 2012). However, empirical evidence for which traits are good predictors of climate change risk is limited in availability and consensus, with many traits commonly used in vulnerability assessments shown to have little to no predictive power (MacLean & Beissinger 2017). It is possible that the combination of traits that would reliably predict risk under climate change are highly species specific, and the use of trait based approaches on diverse sets of species with generic trait inputs, as is commonly attempted currently, simply do not capture a useful combination for most species.

There are also a range of intangible factors that influence which species are prioritised for conservation action, which can be incredibly difficult to incorporate into any formal risk assessment process. Considerations such as the cultural significance of a species or its perceived charisma amongst the general public can affect how conservation resources are spent (Walpole & Leader-Williams 2002; Martín-López et al. 2009), and as these opinions can differ greatly across different countries or regions when considering the same species, producing any quantifiable metric to use in a risk assessment is not a straightforward process. Even considerations such as the economic value a species provides, which can be more readily quantified analytically but likely with high uncertainty, are still not straight forward to include in a risk assessment. For instance in Great Britain recreational hunting of some species has been shown to provide economic benefits, whilst simultaneously being linked to declines of non-target species and conflicts between different organisations regarding management options (Hanley et al. 2010), clearly simply utilising the economic value of a species in a risk assessment process would not capture the nuance of this sort of situation and adds more uncertainty to any conservation prioritisation.

The outputs from species distribution models that are commonly used in climate change vulnerability assessments are another source of uncertainty (Beale & Lennon 2012), as are the different future climate scenarios used to project the models forward in time (Lempert et al. 2004; Garcia et al. 2012; Bagchi et al. 2013). With a wide variety of methods available to generate species distribution models and a huge variety of bioclimate variables readily available for users to include in their models it can be easy to generate outputs with little biological relevance to the species of interest; including this sort of information within a vulnerability assessment will likely produce misleading prioritisations. However, there is a growing body of evidence that if climate envelope modelling is used appropriately with careful selection of biologically relevant variables the outputs can be highly informative of likely changes to species distributions under climate change (Green et al. 2008; Araújo & Peterson 2012; Stephens et al. 2016).

Of course, extinction risk is also not solely driven by the impacts of climate change, with many other factors such as land use change, habitat loss and overexploitation acting as major drivers of species losses globally (Butchart et al. 2010; Frishkoff et al. 2016; Semper-Pascual et al. 2018) How climate change will act to potentially exacerbate the effects of these factors is still a major source of uncertainty when attempting to assess the future risk faced by species (Brook et al. 2008). Most species distribution modelling approaches are designed to project the direct impacts of climate change (Pearce-Higgins et al. 2015b; Engler et al. 2017), but it is much more difficult to incorporate changing pressures from any other external sources as a result of climate change (Brambilla et al. 2018; Guo et al. 2018). This limitation of species distribution modelling may lead to a potential underestimate of future risk for many species, particularly if climate change will introduce additional pressures not already experienced by the species and for which conservation action is unlikely to already be established to help to minimise the negative impacts of these pressures. With the interacting effects of climate change and land use change predicted to lead to a loss of up to 38% of vertebrate species from communities (Newbold 2018), greater incorporation indirect impacts of climate change into future vulnerability assessments will be essential to reduce uncertainty in estimates of risk.

The climate change vulnerability assessment performed in Chapter 3 highlighted large numbers of species at high risk from climate change, which is revealing in terms of the likely impacts of climate change on European biodiversity but is less useful in terms of identifying exactly which species are most in need of conservation action. A long list of species scored in the same risk category and with little to differentiate between them is difficult to prioritise from if resources are limited and only some species can be targeted. This again adds to the difficulty for anyone attempting to utilise the results of climate change risk assessments to inform actual conservation management and is another potentially limiting factor to the wider uptake amongst the conservation community as a planning tool.

It may be more practical to consider broader patterns of risk, particularly those using ensembles of species such as the spatial prioritisation analysis presented in Chapters 3 and 4, as these averaged patterns of risk and opportunity can remove some of the high uncertainty associated with considered single species individually in conservation planning (Lin et al. 2018). Shifting the focus away from protecting individual species and onto ecosystems as a whole rather than single species in conservation planning, could help to simplify the decision making process and allow for more generic conservation action plans to be put in place. If ecosystem services and functions are maintained, even if individual species are lost or replaced, many of the goals conservation management is put in place to aim for could still be achieved. If there is too much focus on preventing individual species extinctions under climate change over the next century then we are likely to experience lots of disappointment.

There is seemingly a general uneasiness within the conservation community around planning based on the results of assessments of future risk for individual species, despite the fact it is commonly how we prioritise species conservation in the face on current known risks and it is seemingly the pragmatic approach to incorporating future risk into this process. Making predictions that a particular species, in a particular location is definitely threatened will inevitably lead to some mistakes, even if on aggregate we get things right about the overall level of threat to biodiversity. Recognising this uncertainty in single species assessments, we might be better off looking at aggregate predictions, such as the spatial prioritisation in Chapters 3 and 4, in general rather than attempting to plan conservation action for a list of individual species.

5.4 Climate change vulnerability assessment limitations

In addition to some of the inherent uncertainty with any approach to assessing future risk from climate change to species, there are some other limitations more specific to my assessments of risk in Chapters 3 and 4. A limitation of my climate change vulnerability assessment in Chapter 3, for the birds particularly, is of the focus on climate change impacts on only the breeding distributions of species, without explicitly including information on the wintering distributions of migratory species (Small-Lorenz et al. 2013). The climate change vulnerability assessment framework used to assign climate change risk categories does include migratory status as one of the exacerbating factors, so species spending some part of their lifecycle outside of Europe have their climate risk score weighted more highly than resident species, but an important component of risk may still not be accurately captured.

With some bird species dependent on relatively geographically constrained wintering areas (Newton 2004) or with limited areas at which they can stop while following their migratory flyways (Huntley et al. 2006), changing climate in these locations could have serious negative effects on European breeding populations if they become unsuitable for the transient bird populations dependent on them. It is also possible that total migratory distances will increase as a result of changes in stopover sites, increasing the total time spent on migration with potential reductions in fitness of individuals as a consequence (Howard et al. 2018). With growing evidence that climate change is already having a strong negative impact on populations of migratory European birds (Gregory et al. 2009), particularly through phenological shifts in the timings of departures leading to mismatches in food availability (Moller et al. 2008; Beresford et al. 2018), any additional impacts of climate change on key wintering locations are likely to further exacerbate these declines. Incorporating these additional climate change threats within the climate change vulnerability assessment process would improve the overall species level prioritisation and allow for more informed conservation decisions to be made.

The climate change vulnerability assessment carried out in Chapter 3 is also limited in how well it incorporates the arrival of colonising species into Europe from the Western Palearctic, as their distributions shift into newly climatically suitable areas. A total of 335 species of birds and butterflies are recorded with breeding distributions within the Western Palearctic, it is plausible that a proportion of these species will be able to persist in regions of novel climate space projected to occur within Europe and will have the required dispersal ability to reach these areas. These potential colonisers are not recorded in the opportunity categories in the climate change vulnerability assessment, but their inclusions could change the overall pattern of risks reported.

The 50 x 50km scale distribution data used for modelling both taxonomic groups are also inherently limited in how accurately it can predict species distributions which may only occupy small percentages of the total area of each cell. With all of the assessments based on this macro scale species distribution modelling I am only able to make predictions of potential future risk based on broad patterns of distribution shifts, which may be missing some important fine scale detail. With microclimates within a landscape offering upwards of 1°C of variation in temperature over relatively short distances (Maclean et al. 2017), this fine-grain heterogeneity in climate may allow species to persist in localities my macro models project will become unsuitable (Rull 2009; Hannah et al. 2014), with suggestions that microclimate buffering might reduce extinction risk at some localities by up to 22% (Suggitt et al. 2018). With the spatial prioritisations for Europe highlighting the continuing importance of montane regions in particular, the large microclimate gradients in these areas are unlikely to be fully captured at the scale I am modelling at and some species projected to be at high risk due to climate space in these areas becoming unsuitable may actually be able to persist in reality due to the presence of these microrefugia. The 50 x 50 km resolution models were also used for the spatial prioritisation analysis, which is too broad a spatial scale to make practical, on the ground conservation management decisions. The broad patterns of change in priority areas, as well as the drivers behind those changes, should still be of value to conservation decision makers as they highlight currently underrepresented regions and can be used to start early discussions of future conservation planning under climate change.

My assessments of both species level risk as well as broader geographic patterns of risk are based on just two taxonomic groups, representing only a very small fraction of the terrestrial biodiversity present across Europe. As responses to and risk from climate change can vary widely between different taxonomic groups (Foden et al. 2008), a more diverse range of species will need to be assessed using a climate change vulnerability assessment to give a more accurate prognosis of the potential impacts of climate change on European biodiversity. However, birds in particular have been shown to be useful surrogates for a wide range of biodiversity when planning conservation action and focussing on protecting them can lead to benefits for other taxonomic groups as well (Roberge & Angelstam 2004; Gregory et al. 2005; Larsen et al. 2012; Kukkala et al. 2016). Both birds and butterflies also demonstrated broadly similar priority areas in the spatial prioritisations, as well as the same shift in priority areas under climate change which would suggest other taxonomic groups may be expected to also respond similarly. Protected areas have also been shown to provide a range of benefits and are often key sites for species they were not originally designated to protect (Butchart et al. 2012, 2015; Di Marco et al. 2015), again suggesting that the focus on just two taxonomic groups in this thesis should not be too limiting on the overall implications for conservation in Europe under climate change.

5.6 Recommendations for conservation and future research

A variety of actions and continuing work will be required in order to try and limit the impacts of climate change on biodiversity. One major component of work that will be required is the ongoing and expanded monitoring of species distributions to ensure the impacts of climate change on biodiversity can be adequately recorded and addressed by conservation action. Accurate and geographically comprehensive distribution records are crucial to ensuring that projected species distributions models can perform well (Araújo & Guisan 2006) and be informative when used to guide conservation decision making, so ensuring existing monitoring schemes are maintained and new schemes established will be important.

Continuing development of species distribution modelling techniques will also be beneficial in improving our predictions of risk from climate change. This is an area of research that has been continually evolving for more than a decade already (Guisan & Thuiller 2005; Araújo & Guisan 2006; Araújo & Peterson 2012), but improved model outputs and further validation of these outputs will make predictions of climate change risk more useful and more likely to be utilized in conservation decision making processes. Advances in computing power and cluster computing becoming more widely available should help to make large scale species distribution modelling more accessible to a wider community of experts, but optimisation of code and modelling methods/techniques will still be required to ensure existing tools are useful and widely applicable to different regions and taxonomic groups.

Climate change vulnerability assessments should be viewed as a continually developed and updated process; similar to how the IUCN Red List is periodically reviewed and updated with new data as it becomes available. At present climate change vulnerability assessments are most commonly presented as one off, standalone pieces of work which can quickly become outdated and unusable for practical conservation purposes, and this is an issue that needs to be addressed. These assessments are designed to act as an early warning system for potential negative impacts of climate change on individual species, without regular updates to species distribution modelling and exacerbating factor data they will not remain fit for purpose for very long.

There is a need to incorporate more taxonomic groups into the climate vulnerability assessment process, at present vertebrates (and birds in particular) are disproportionately represented and many taxonomic groups are receiving little attention at all in terms of identifying climate change risk (Pacifici et al. 2015). This issue is partly driven by the lack of detailed distribution data for the majority of species globally, so expanding the coverage of existing monitoring schemes to cover new locations and new taxonomic groups as previously suggested will be a first step towards addressing this imbalance. However, given the likelihood that the data required to perform these assessments will not be available in time, or ever, for many species, there must also be some careful consideration given to whether single species vulnerability assessments are a sensible prioritisation option at all. Increased usage of spatial prioritisation type approaches or use of indicator species to assess future risk may be less resource intensive than attempting to prioritise for all species individually, and could still produce positive conservation outcomes for a wide range of species as well as reducing some of the associated uncertainty previously discussed.

In terms of ensuring climate change vulnerability assessments can have any sort of impact in reducing species losses under climate change, engagement with conservation practitioners and policy makers to ensure the results assessments are incorporated into the conservation planning process will be required. There is currently little evidence that the results of any climate change vulnerability assessment have been successfully used to prioritise conservation action for a species, with traditional vulnerability assessments based on observed changes and with potentially less uncertainty seemingly being preferred when setting priority species' lists. Developing methods to incorporate a comprehensive and robust measure of climate change risk as a component within already established and accepted vulnerability assessments may be required, but efforts should still be made to encourage practitioners to utilise standalone climate change vulnerability assessments as part of their routine planning process for conservation action.

Another issue that will require continued work and discussion with policy makers and conservation practitioners is to improve the integration of conservation management across borders to maximise the impact of resources being spent to implement on the ground conservation for species. There is evidence that national level planning based on regional Red List assessments may potentially underestimate the relative importance of populations of a species in a wider geographical context, leading to limited conservation action to protect internationally important sites (Keller & Bollmann 2004). There are also suggestions that as the Red List assessment process was designed to work at a global scale, using it to generate national level assessments can lead to inaccuracies, further reducing the effectiveness of national only conservation planning (Gardenfors et al. 2001; Popov et al. 2017; Vignoli et al. 2017; Do et al. 2018), although the majority of national level Red List assessments correlate well with the threat status assigned from global assessments (Brito et al. 2010). This is the same issue highlighted by the differences in effectiveness of the fully joined up continental scale and national only scale spatial prioritisations in Chapter 4, with the continental scale approach incorporating the relative importance of species across Europe into the analysis and producing a more coherent set of priority areas.

5.7 Concluding remarks

It is clear that climate change will lead to a large-scale redistribution of species across Europe by the end of the century. The differences in terms of impact between the lowest and highest magnitude scenarios for future climate change are not that pronounced, as evidenced in the results of both the species level vulnerability assessments and when setting spatial priority areas across the continent. This would suggest that even under the best-case climate scenario, which current evidence indicates we are highly unlikely to limit our emissions trajectory to be able to achieve, there will be dramatic effects on biodiversity across Europe. Regardless of whether individual species will benefit or decline, very few are projected to experience a limited impact to their distributions as a result of these changing conditions and difficult conservation decisions will need to be made about what conservation action is taken in order to ensure the maximum amount of biodiversity is protected going forward.

Although many of the messages around the impacts of climate change have focussed on the projected declines and possible extinctions of species as a consequence of changing conditions, this climate change vulnerability assessment demonstrates that there will also potential beneficiaries as well. The wide range of species predicted to expand their distributions or continue to persist in existing locations under climate change, coupled with the potential for new colonisations by species not currently present in the region, would suggest that there are many potential opportunities for biodiversity conservation success stories across Europe.

There are reasons to be hopeful that, although climate change will bring about inevitable changes to the species composition of Europe, we can take action to mitigate any overall negative effects on biodiversity. Over the course of this century, we have the opportunity to limit the negative impacts of climate change on many species and realise the potential benefits it holds for others, if conservation action is implemented proactively and greater cooperation between governments is achieved when planning and implementing conservation management options across the continent.

Appendix

Figure S2.1. Frequency distributions of risk category assignment. Comparison of risk output distribution of each of the 12 frameworks for 10,000 randomly generated trait sets ('simulated species'), following standardization of categories to a Low/Medium/High scale. The overall pattern is for most frameworks to classify the majority of species as low risk, with the lowest number of species assigned to the highest risk category.

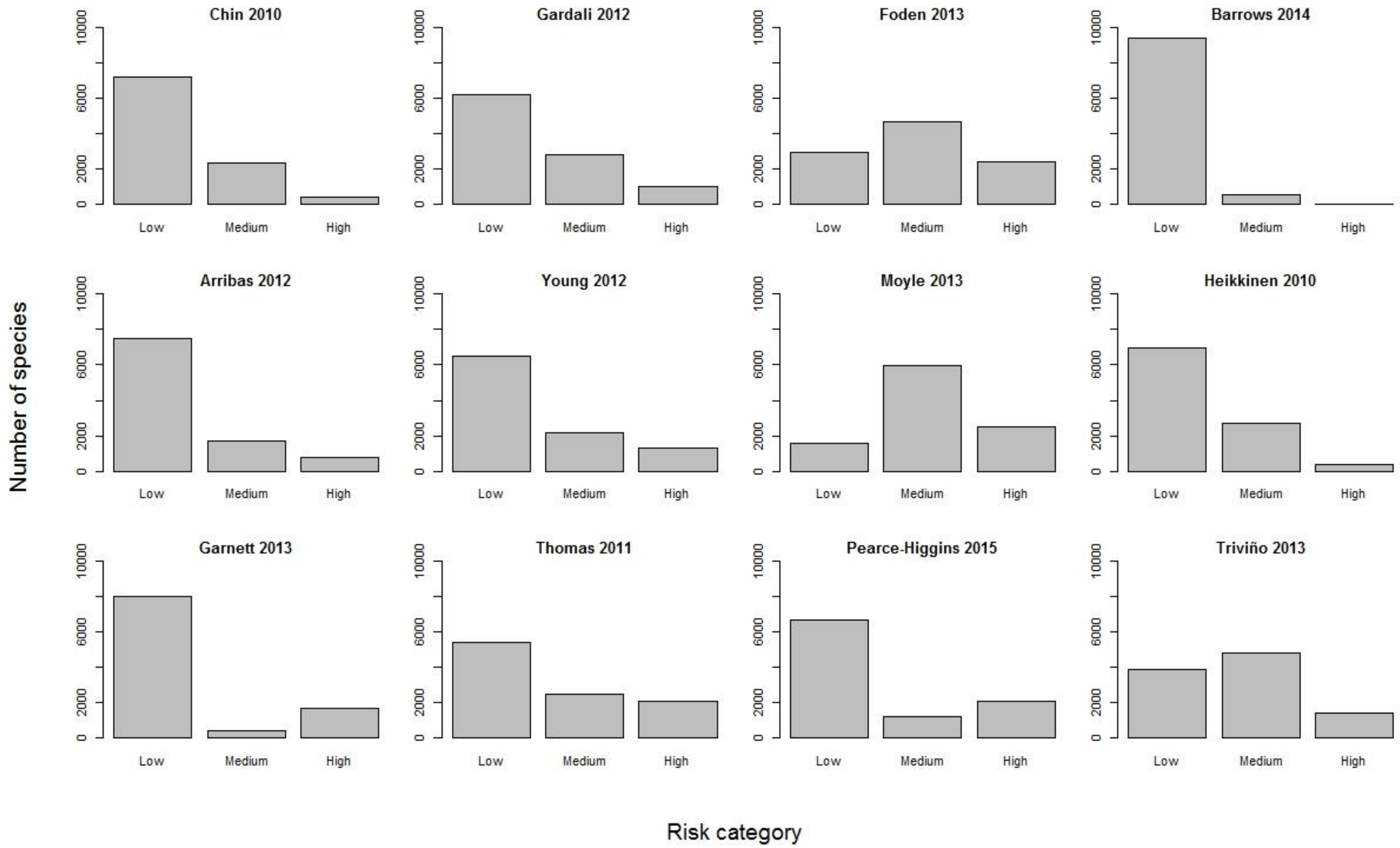


Figure S2.2. Validation boxplots showing logged change in bird population against simplified risk category for each of the 12 risk assessment frameworks. Blue lines show a significant trend in the 0.5 quantile and green lines show a significant trend in the 0.75 quantile.

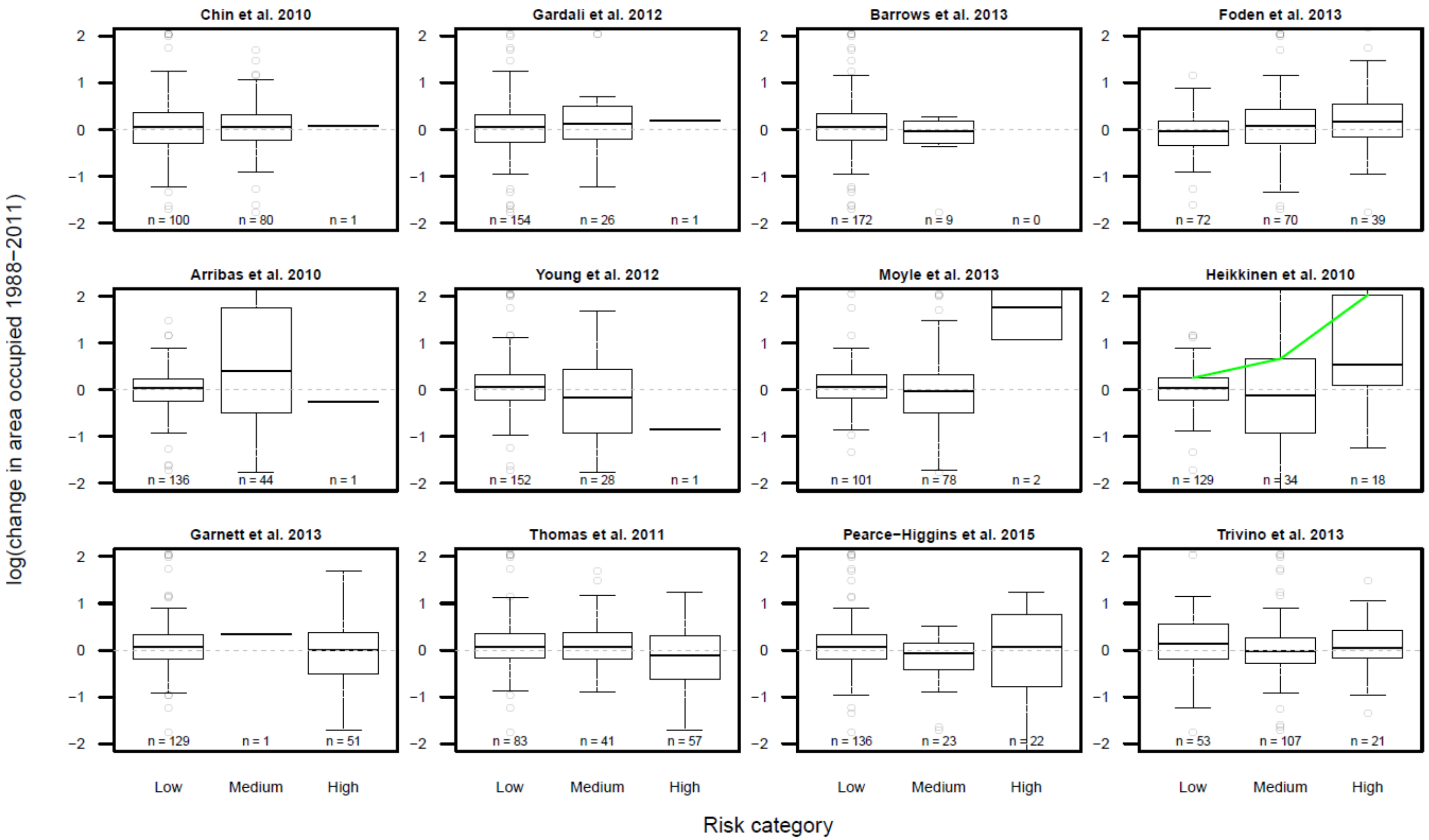


Figure S2.3. Validation boxplots showing logged change in butterfly population against simplified risk category for each of the 12 risk assessment frameworks. Blue lines show a significant trend in the 0.5 quantile and green lines show a significant trend in the 0.75 quantile.

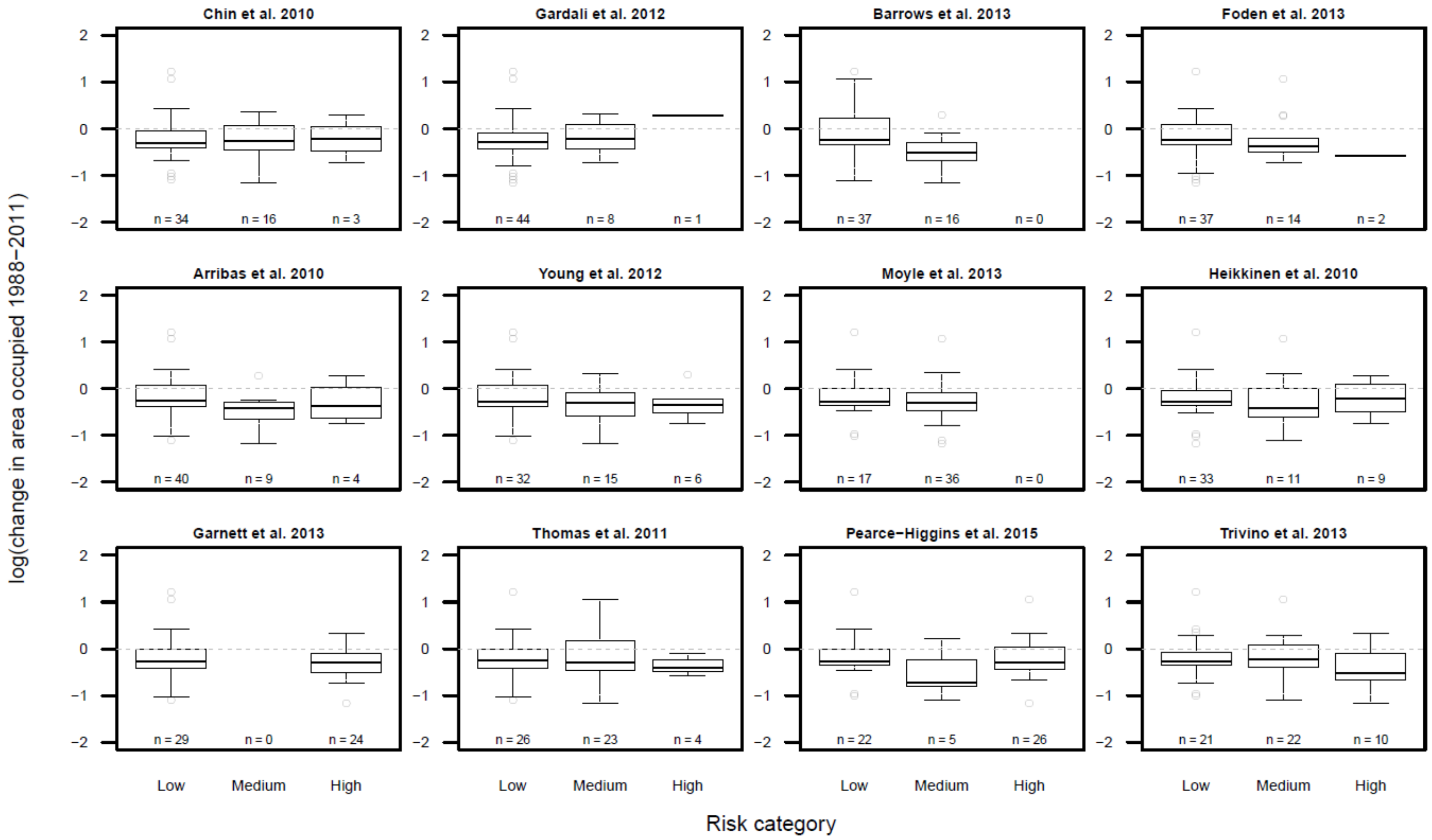


Figure S2.4. Validation boxplots showing a) logged change in bird distribution, b) logged change in bird population and c) logged change in butterfly population against maximum simplified risk category from across all 12 risk assessment frameworks.

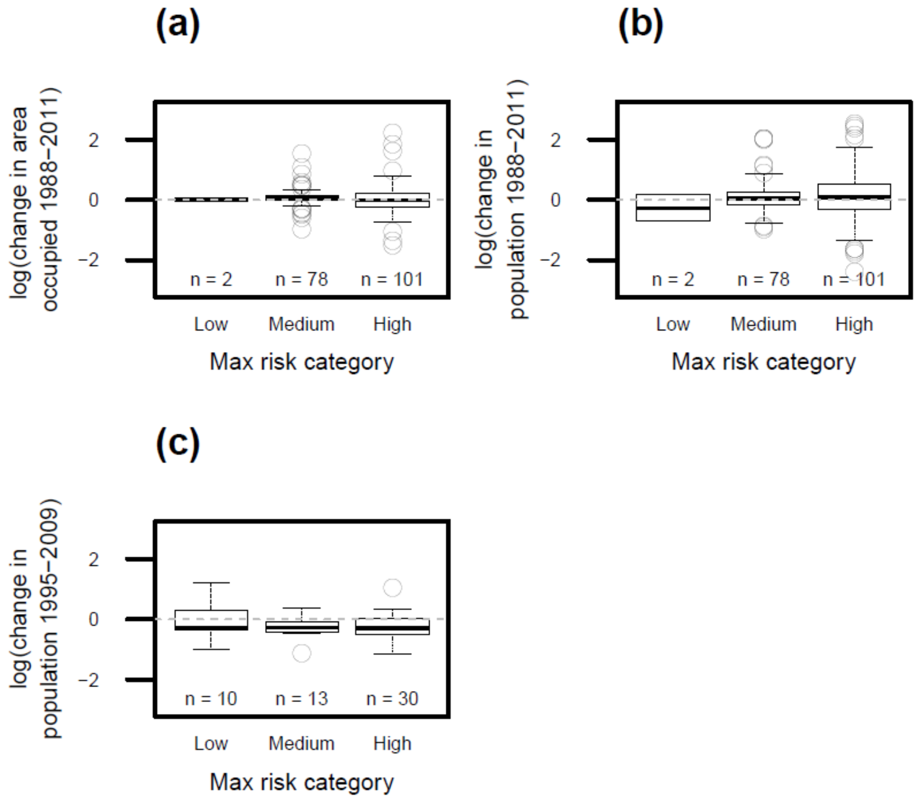


Table S2.1. Input variables required to run each of the 12 climate change vulnerability assessment frameworks and the framework they originate from. Some variable are required by multiple frameworks, and many of the variables are qualitative metrics without clear numerical definition in the original framework.

Input Variable	Framework
Physiological tolerances	
Narrow temperature tolerance (Average absolute deviation in temperature across the species' historical range)	Foden et al. 2013
Narrow precipitation tolerance (Average absolute deviation in precipitation across the species' historical range)	Foden et al. 2013
Substantial changes in temperature variability across the species' range - Absolute difference between average absolute deviation in temperatures across the species' range for all months)	Foden et al. 2013
Substantial changes in mean temperature occur across the species' range - Absolute difference between (mean temperatures across the species' range for all months) from 1975- 2050 (°C)	Foden et al. 2013
Substantial changes in mean precipitation occur across the species' range - Absolute ratio of change in (mean precipitation across the species' range for all months) from 1975 to 2050	Foden et al. 2013
Absolute ratio of change in (average absolute deviation in precipitation across the species' range for all months)	Foden et al. 2013
Temperature variation in historic range (highest mean monthly temp - lowest mean monthly temp)	Chin et al. 2010, Gardali et al. 2012, Moyle et al. 2013, Young et al. 2012
Precipitation variation in historic range (highest mean annual precipitation - lowest mean annual precipitation)	Chin et al. 2010, Gardali et al. 2012, Moyle et al. 2013, Young et al. 2012
Area of range/extent restricted to relatively cool or cold environments (high elevation, northernmost areas etc.) in assessment area (%)	Young et al. 2012
Expected direction of moisture change (drier or wetter) likely to reduce species abundance/distribution/habitat quality	Young et al. 2012
Habitat	
Number of habitats	Chin et al. 2010, Foden et al. 2013, Gardali et al. 2012, Heikkinen et al. 2010, Moyle et al. 2013
Microhabitat dependency	Foden et al. 2013
Intolerant of disturbance	Foden et al. 2013
Dependence on a specific disturbance regime likely to be impacted by climate change	Young et al. 2012
Area of range dependent on ice, ice-edge, or snow cover habitats (%)	Young et al. 2012
Area of range/extent dependent on specific wetland/aquatic habitat (%)	Young et al. 2012

Change in area of suitable habitat (%)	Gardali et al. 2012, Moyle et al. 2013
Habitat exposed to sea level rise (%)	Foden et al. 2013, Young et al. 2012
Intertidal habitat predicted to increase	Young et al. 2012
Low habitat availability in future climate space - climate based expansion	Thomas et al. 2011
Occupied grid cells - Hostile land (%)	Heikkinen et al. 2010
Occupied grid cells - Cultivated land (%)	Heikkinen et al. 2010
200 km buffer - Hostile land (%)	Heikkinen et al. 2010
200 km buffer - Cultivated land (%)	Heikkinen et al. 2010
Topographic heterogeneity	Heikkinen et al. 2010
Habitat specificity	Heikkinen et al. 2010
Overlap between habitat and climate change	Chin et al. 2010, Moyle et al. 2013
Habitat breadth	Triviño et al. 2013
Restriction to uncommon geological features or derivatives	Young et al. 2012
Marginality	Triviño et al. 2013
Impact of land use changes designed to mitigate against climate change	Young et al. 2012
Habitat composition change	Barrows et al. 2014
Habitat quality change	Barrows et al. 2014
Habitat contracting - observed	Thomas et al. 2011
Specific habitat associated threats - projected	Thomas et al. 2011
Dispersal	
Dispersal capacity (km)	Arribas et al. 2012, Barrows et al. 2014, Chin et al. 2010, Foden et al. 2013, Gardali et al. 2012, Moyle et al. 2013, Thomas et al. 2011, Young et al. 2012
Dispersal ability	Heikkinen et al. 2010

Migratory status	Gardali et al. 2012
% area dispersal barriers	Foden et al. 2013, Young et al. 2012
Are there anthropogenic constraints to this species' dispersal to reach shifts in suitable habitat?	Barrows et al. 2014
Distribution relative to natural topographic or geographic habitat barriers	Young et al. 2012
Distribution relative to anthropogenic barriers	Barrows et al. 2014, Young et al. 2012t
Life History	
Turnover of generations	Foden et al. 2013, Moyle et al. 2013
Reproductive capacity	Foden et al. 2013, Triviño et al. 2013
Food availability change	Gardali et al. 2012
Dietary versatility	Chin et al. 2010,Young et al. 2012
Body length	Triviño et al. 2013
Mean no. broods	Triviño et al. 2013
Relative brain size	Garnett 2013
Genetic variation	Foden et al. 2013, Young et al. 2012
Occurrence of bottlenecks in recent evolutionary history	Young et al. 2012
Population/Range	
Population size - observed	Chin et al. 2010, Foden et al. 2013, Moyle et al. 2013, Thomas et al. 2011
Population size - projected	Thomas et al. 2011
number of colonies - observed	Thomas et al. 2011
number of colonies - projected	Thomas et al. 2011
Extent - observed	Thomas et al. 2011
Extent - projected	Thomas et al. 2011
Area Occupied - observed	Thomas et al. 2011, Triviño et al. 2013

Area Occupied - projected	Thomas et al. 2011, Triviño et al. 2013
Decline in distribution per decade (%) - observed	Pearce-Higgins et al. 2015, Thomas et al. 2011
Decline in abundance per decade (%) - observed	Pearce-Higgins et al. 2015, Thomas et al. 2011
Increase in distribution per decade (%) - observed	Pearce-Higgins et al. 2015, Thomas et al. 2011
Increase in abundance per decade (%) - observed	Pearce-Higgins et al. 2015, Thomas et al. 2011
Linkage between decline and climate - observed	Thomas et al. 2011
Decline in distribution per decade (%) -projected	Pearce-Higgins et al. 2015, Thomas et al. 2011
Decline in abundance per decade (%) - projected	Pearce-Higgins et al. 2015, Thomas et al. 2011
Increase in distribution per decade (%) - expansion	Pearce-Higgins et al. 2015, Thomas et al. 2011
Increase in abundance per decade (%) - expansion	Pearce-Higgins et al. 2015, Thomas et al. 2011
Linkage between increase and climate - expansion	Thomas et al. 2011
Increase in distribution per decade (%) - climate based expansion	Pearce-Higgins et al. 2015, Thomas et al. 2011
Increase in abundance per decade (%) - climate based expansion	Pearce-Higgins et al. 2015, Thomas et al. 2011
Latitudinal range	Chin et al. 2010
Range shift, full dispersal	Heikkinen et al. 2010
Range shift, no dispersal	Heikkinen et al. 2010
Nearest cell	Heikkinen et al. 2010
Prevalence	Triviño et al. 2013
Change in range in modelled future distribution (%)	Triviño et al. 2013, Young et al. 2012
Change in population in modelled future distribution (%)	Young et al. 2012
Overlap of modelled future (2050) range with current range (%)	Young et al. 2012

Area of protected areas in modelled future distribution (%)	Young et al. 2012
Current population trend	Moyle et al. 2013
Long term population trend	Moyle et al. 2013
Current range trend	Moyle et al. 2013
Long term range trend	Moyle et al. 2013
Interspecific Interactions	
Dependence on interspecific interactions	Foden et al. 2013
Declining host - observed	Thomas et al. 2011
Declining host - projected	Thomas et al. 2011
Expanding enemy - observed	Thomas et al. 2011
Expanding enemy - projected	Thomas et al. 2011
Other species specific losses - observed	Thomas et al. 2011
Other species specific losses - projected	Thomas et al. 2011
Other limiting species/other species specific constraints limiting expansion - climate based expansion	Thomas et al. 2011
Dependence on other species to generate habitat	Young et al. 2012
Forms part of a mutualism	Young et al. 2012
Predators/Parasites/Insect herbivores: Are populations for these trophic levels expected to change with respect to this species?	Barrows et al. 2014
Climate	
Climatic suitability	Heikkinen et al. 2010
Change in extreme weather	Gardali et al. 2012, Moyle et al. 2013
Climatic niche breadth	Triviño et al. 2013
Temperature exposure	Young et al. 2012
Precipitation exposure	Young et al. 2012

Overlap between range and climate change	Chin et al. 2010
Phenology	
Phenological response to changing seasonal temperature and precipitation regimes	Young et al. 2012
Does this species use temperature or moisture cues to initiate germination, hibernation or reproductive activity?	Barrows et al. 2014
Event timing. Are activities related to species' fecundity or survival tied to discrete peaks in available resources that are likely to change?	Barrows et al. 2014
Are projected climate shifts expected to influence activity patterns or phenology?	Barrows et al. 2014
Does this species have flexible strategies to cope with limiting resources over multiple years?	Barrows et al. 2014
Disease likelihood change?	Barrows et al. 2014
Conservation status	
Global IUCN conservation status	Triviño et al. 2013
Regional conservation status	Triviño et al. 2013
Endemic to region	Triviño et al. 2013
Keystone species?	Barrows et al. 2014
Current dependence on human intervention	Moyle et al. 2013
Other	
Current stressors other than climate	Moyle et al. 2013
Future stressors other than climate	Moyle et al. 2013
Dependence on exogenous factors	Moyle et al. 2013
Does this species engender interest among visitors regarding its well-being?	Barrows et al. 2014
Does this species provide an important ecosystem function?	Barrows et al. 2014

Table S2.2. Simplified risk categories used in this study. Low/Medium/High risk categories and the original risk categorisations from each of the 12 frameworks used to produce them.

Framework	Low risk	Medium risk	High risk
Chin et al. 2010	Low	Moderate	High
Gardali et al. 2013	Unprioritized, Low	Moderate	High
Foden et al. 2013	None, Low adaptive capacity only, Exposed only, Sensitive only	High latent risk, Potential persisters, Potential adapters	Highly vulnerable
Barrows et al. 2014	Resilient, Likely resilient, Neutral	Likely vulnerable	Vulnerable
Arribas et al.2012	Conservation efforts in current localities	Conservation of habitat patches extending to future area, Increase connectivity of suitable areas	Intense measures to maintain populations
Young et al. 2012	Increase Likely, Presumed Stable	Moderately Vulnerable	Highly Vulnerable, Extremely Vulnerable
Moyle et al. 2013	Least vulnerable	Less vulnerable	Highly vulnerable, Critically vulnerable
Heikkinen et al. 2010	0 - 1	2 – 3	4 +
Garnett et al. 2013	Low	Medium	High
Thomas et al. 2011	Limited impact, High opportunity, Medium opportunity, Risks and opportunity	Medium risk	High risk
Pearce-Higgins et al. 2015	Limited impact, High opportunity, Medium opportunity, Risks and opportunity	Medium risk	High risk
Triviño et al. 2013	Not exposed and not threatened	Exposed and not threatened, Not exposed and threatened	Exposed and threatened

Table S2.3. Risk assessment output for exemplar real species Low (*white*), Medium (*grey*) and High (*black*) risk category outputs for each of the 18 exemplar species assessed using all 12 climate change vulnerability assessment frameworks. Assessments were carried out for Great Britain based upon contemporary data. Comparable to Table 2 (main text), but with modelled future distributions based upon a low emission scenario (B1 projection for 2070-2099). Northern or southern distributed species are identified in the distribution column.

Birds	**Distribution**	**Chin**	**Gardali**	**Foden**	**Barrows**	**Arribas**	**Young**	**Moyle**	**Heikkinen**	**Garnett**	**Thomas**	**Pearce-Higgins**	**Triviño**
Black grouse (*Tetrao tetrix*)	**N**												
Capercaillie (*Tetrao urogallus*)	**N**												
Black-throated diver (*Gavia arctica*)	**N**												
Common scoter (*Melanitta nigra*)	**N**												
Red-throated diver (*Gavia stellata*)	**N**												
Slavonian grebe (*Podiceps auritus*)	**N**												
Bittern (*Botaurus stellaris*)	**S**												
Dartford warbler (*Sylvia undata*)	**S**												
Nightjar (*Caprimulgus europaeus*)	**S**												
Stone curlew (*Burhinus oedicnemus*)	**S**												
Woodlark (*Lullula arborea*)	**S**												
Butterflies													
Large heath (*Coenonympha tullia*)	**N**												
Mountain ringlet (*Erebia epiphron*)	**N**												
Northern brown argus (*Aricia artaxerxes*)	**N**												
Scotch argus (*Erebia aethiops*)	**N**												
Adonis blue (*Polyommatus bellargus*)	**S**												
Large Blue *(Maculina arion)*	**S**												
Silver-spotted skipper (*Hesperia comma*)	**S**												

Table S2.4. Risk assessment output for British bird and butterfly species. Low (*white*), Medium (*grey*) and High (*black*) risk category outputs for each of the 181 British bird and 53 butterfly species assessed using all 12 climate change vulnerability assessment frameworks. Assessments were carried out for Great Britain, with modelled future distributions based upon a medium emission scenario (*A1B projection for 2070-2099*). The assessments are based on historic data and evidence from the early 1990s and are for comparative purposes only; they should not be regarded as providing a current assessment or used to form the basis of any current day conservation actions.

	Chin	Gardali	Foden	Barrows	Arribas	Young	Moyle	Heikkinen	Garnett	Thomas	Pearce-Higgins	Triviño
Birds												
Arctic Tern (*Sterna paradisaea*)												
Avocet (*Recurvirostra avosetta*)												
Barn Owl (*Tyto alba*)												
Bearded Tit (*Panurus biarmicus*)												
Bittern (*Botaurus stellaris*)												
Black grouse (*Tetrao tetrix*)												
Black Guillemot (*Cepphus grylle*)												
Black Redstart (*Phoenicurus ochruros*)												
Blackbird (*Turdus merula*)												
Blackcap (*Sylvia atricapilla*)												
Black-headed Gull (*Chroicocephalus ridibundus*)												
Black-tailed Godwit (*Limosa limosa*)												
Blue Tit (*Cyanistes caeruleus*)												
Black-throated diver (*Gavia arctica*)												
Bullfinch (*Pyrrhula pyrrhula*)												
Buzzard (*Buteo buteo*)												
Canada Goose (*Branta canadensis*)												
Carrion Crow (*Corvus corone*)												
Cetti’s Warbler (*Cettia cetti*)												
Chaffinch (*Fringilla coelebs*)												

Chiffchaff (*Phylloscopus collybita*)												
Cirl Bunting (*Emberiza cirlus*)												
Coal Tit (*Periparus ater*)												
Collared Dove (*Streptopelia decaocto*)												
Common Crossbill (*Loxia curvirostra*)												
Common Gull (*Larus canus*)												
Common Sandpiper (*Actitis hypoleucos*)												
Common Tern (*Sterna hirundo*)												
Common scoter (Melanitta nigra)												
Coot (*Fulica atra*)												
Cormorant (*Phalacrocorax carbo*)												
Corn Bunting (*Emberiza calandra*)												
Corncrake (*Crex crex*)												
Cuckoo (*Cuculus canorus*)												
Curlew (*Numenius arquata*)												
Dartford warbler (*Sylvia undata*)												
Dipper (*Cinclus cinclus*)												
Dotterel (*Charadrius morinellus*)												
Dunlin (*Calidris alpina*)												
Dunnock (*Prunella modularis*)												
Egyptian Goose (*Alopochen aegyptiaca*)												
Eider (*Somateria mollissima*)												
Fieldfare (*Turdus pilaris*)												
Firecrest (*Regulus ignicapilla*)												
Fulmar (*Fulmarus glacialis*)												
Gadwall (*Anas strepera*)												
Gannet (*Morus bassanus*)												
Garden Warbler (*Sylvia borin*)												

Garganey (*Anas querquedula*)												
Goldcrest (*Regulus regulus*)												
Golden Eagle (*Aquila chrysaetos*)												
Golden Pheasant (*Chrysolophus pictus*)												
Golden Plover (*Pluvialis apricaria*)												
Goldeneye (*Bucephala clangula*)												
Goldfinch (*Carduelis carduelis*)												
Goosander (*Mergus merganser*)												
Goshawk (*Accipiter gentilis*)												
Grasshopper Warbler (*Locustella naevia*)												
Great Black-backed Gull (*Larus marinus*)												
Great Crested Grebe (*Podiceps cristatus*)												
Great Spotted Woodpecker (*Dendrocopos major*)												
Great Tit (*Parus major*)												
Green Woodpecker (*Picus viridis*)												
Greenfinch (*Chloris chloris*)												
Grey Heron (*Ardea cinerea*)												
Grey Partridge (*Perdix perdix*)												
Grey Wagtail (*Motacilla cinerea*)												
Greylag Goose (*Anser anser*)												
Guillemot (*Uria aalge*)												
Hawfinch (*Coccothraustes coccothraustes*)												
Hen Harrier (*Circus cyaneus*)												
Herring Gull (*Larus argentatus*)												
Hobby (*Falco subbuteo*)												
House Martin (*Delichon urbicum*)												
House Sparrow (*Passer domesticus*)												
Jackdaw (*Corvus monedula*)												

Jay (*Garrulus glandarius*)												
Kestrel (*Falco tinnunculus*)												
Kingfisher (*Alcedo atthis*)												
Kittiwake (*Rissa tridactyla*)												
Lapwing (*Vanellus vanellus*)												
Lesser Black-backed Gull (*Larus fuscus*)												
Lesser Spotted Woodpecker (*Dendrocopos minor*)												
Lesser Whitethroat (*Sylvia curruca*)												
Linnet (*Linaria cannabina*)												
Little Grebe (*Tachybaptus ruficollis*)												
Little Owl (*Athene noctua*)												
Little Ringed Plover (*Charadrius dubius*)												
Little Tern (*Sternula albifrons*)												
Long-eared Owl (*Asio otus*)												
Long-tailed Tit (*Aegithalos caudatus*)												
Mallard (*Anas platyrhynchos*)												
Mandarin (*Aix galericulata*)												
Manx Shearwater (*Puffinus puffinus*)												
Marsh Harrier (*Circus aeruginosus*)												
Marsh Tit (*Poecile palustris*)												
Mediterranean Gull (*Larus melanocephalus*)												
Merlin (*Falco columbarius*)												
Mistle Thrush (*Turdus viscivorus*)												
Montagu’s Harrier (*Circus pygargus*)												
Moorhen (*Gallinula chloropus*)												
Mute Swan (*Cygnus olor*)												
Nightingale (*Luscinia megarhynchos*)												

Nightjar (*Caprimulgus europaeus*)												
Nuthatch (*Sitta europaea*)												
Oystercatcher (*Haematopus ostralegus*)												
Peregrine (*Falco peregrinus*)												
Pheasant (*Phasianus colchicus*)												
Pied Flycatcher (*Ficedula hypoleuca*)												
Pied Wagtail (*Motacilla alba*)												
Pintail (*Anas acuta*)												
Pochard (*Aythya ferina*)												
Puffin (*Fratercula arctica*)												
Quail (*Coturnix coturnix*)												
Raven (*Corvus corax*)												
Razorbill (*Alca torda*)												
Red Grouse (*Lagopus lagopus*)												
Red-backed Shrike (*Lanius collurio*)												
Red-breasted Merganser (*Mergus serrator*)												
Red-legged Partridge (*Alectoris rufa*)												
Redshank (*Tringa totanus*)												
Redstart (*Phoenicurus phoenicurus*)												
Red-throated diver (*Gavia stellata*)												
Redwing (*Turdus iliacus*)												
Reed Bunting (*Emberiza schoeniclus*)												
Reed Warbler (*Acrocephalus scirpaceus*)												
Ring Ouzel (*Turdus torquatus*)												
Ringed Plover (*Charadrius hiaticula*)												
Ring-necked Parakeet (*Psittacula krameri*)												
Robin (*Erithacus rubecula*)												
Rock Dove (*Columba livia*)												

Rock Pipit (*Anthus petrosus*)												
Rook (*Corvus frugilegus*)												
Roseate Tern (*Sterna dougallii*)												
Ruddy Duck (*Oxyura jamaicensis*)												
Ruff (*Calidris pugnax*)												
Sand Martin (*Riparia riparia*)												
Sandwich Tern (*Sterna sandvicensis*)												
Savi's Warbler (*Locustella luscinioides*)												
Sedge Warbler (*Acrocephalus schoenobaenus*)												
Shag (*Phalacrocorax aristotelis*)												
Shelduck (*Tadorna tadorna*)												
Short-eared Owl (*Asio flammeus*)												
Shoveler (*Anas clypeata*)												
Siskin (*Spinus spinus*)												
Skylark (*Alauda arvensis*)												
Slavonian grebe (*Podiceps auritus*)												
Snipe (*Gallinago gallinago*)												
Song Thrush (*Turdus philomelos*)												
Sparrowhawk (*Accipiter nisus*)												
Spotted Crake (*Porzana porzana*)												
Spotted Flycatcher (*Muscicapa striata*)												
Starling (*Sturnus vulgaris*)												
Stock Dove (*Columba oenas*)												
Stonechat (*Saxicola rubicola*)												
Stone curlew (*Burhinus oedicnemus*)												
Storm Petrel (*Hydrobates pelagicus*)												
Swallow (*Hirundo rustica*)												
Swift (*Apus apus*)												

Tawny Owl (*Strix aluco*)												
Teal (*Anas crecca*)												
Tree Pipit (*Anthus trivialis*)												
Tree Sparrow (*Passer montanus*)												
Treecreeper (*Certhia familiaris*)												
Tufted Duck (*Aythya fuligula*)												
Turtle Dove (*Streptopelia turtur*)												
Twite (*Linaria flavirostris*)												
Water Rail (*Rallus aquaticus*)												
Wheatear (*Oenanthe oenanthe*)												
Whinchat (*Saxicola rubetra*)												
Whitethroat (*Sylvia communis*)												
Wigeon (*Anas penelope*)												
Willow Tit (*Poecile montana*)												
Willow Warbler (*Phylloscopus trochilus*)												
Woodlark (*Lullula arborea*)												
Woodpigeon (*Columba palumbus*)												
Wood Warbler (*Phylloscopus sibilatrix*)												
Woodcock (*Scolopax rusticola*)												
Wren (*Troglodytes troglodytes*)												
Yellow Wagtail (*Motacilla flava*)												
Yellowhammer (*Emberiza citrinella*)												
Butterflies												
Adonis blue (*Polyommatus bellargus*)												
Black Hairstreak (*Satyrium pruni*)												
Brimstone (*Gonepteryx rhamni*)												
Brown Argus (*Aricia agestis*)												
Brown Hairstreak (*Thecla betulae*)												

Chalkhill Blue (*Lysandra coridon*)												
Chequered Skipper (*Carterocephalus palaemon*)												
Clouded Yellow (*Colias croceus*)												
Comma (*Polygonia c-album*)												
Common Blue (*Polyommatus icarus*)												
Dark Green Fritillary (*Argynnis aglaja*)												
Dingy Skipper (*Erynnis tages*)												
Duke of Burgundy (*Hamearis lucina*)												
Essex Skipper (*Thymelicus lineola*)												
Gatekeeper (*Pyronia tithonus*)												
Grayling (*Hipparchia semele*)												
Green Hairstreak (*Callophrys rubi*)												
Green-veined White (*Pieris napi*)												
Grizzled Skipper (*Pyrgus malvae*)												
Heath Fritillary (*Melitaea athalia*)												
High Brown Fritillary (*Argynnis adippe*)												
Holly Blue (*Celastrina argiolus*)												
Large heath (*Coenonympha tullia*)												
Large Skipper (*Ochlodes faunus*)												
Large White (*Pieris brassicae*)												
Lulworth Skipper (*Thymelicus acteon*)												
Marbled White (*Melanargia galathea*)												
Meadow Brown (*Maniola jurtina*)												
Mountain ringlet (*Erebia epiphron*)												
Northern brown argus (*Aricia artaxerxes*)												
Orange-tip (*Anthocharis cardamines*)												
Painted Lady (*Vanessa cardui*)												
Peacock (*Inachis io*)												

Purple Emperor (*Apatura iris*)												
Purple Hairstreak (*Neozephyrus quercus*)												
Red Admiral (*Vanessa atalanta*)												
Ringlet (*Aphantopus hyperantus*)												
Scotch argus (*Erebia aethiops*)												
Silver-spotted skipper (*Hesperia comma*)												
Silver-studded Blue (*Plebeius argus*)												
Silver-washed Fritillary (*Argynnis paphia*)												
Small Blue (*Cupido minimus*)												
Small Copper (*Lycaena phlaeas*)												
Small Heath (*Coenonympha pamphilus*)												
Small Pearl-bordered Fritillary (*Boloria selene*)												
Small Skipper (*Thymelicus sylvestris*)												
Small Tortoiseshell (*Aglais urticae*)												
Small White (*Pieris rapae*)												
Speckled Wood (*Parage aegeria*)												
Wall (*Lasiommata megera*)												
White Admiral (*Limenitis camilla*)												
White-letter Hairstreak (*Satyrium w-album*)												
Wood White (*Leptidea sinapis*)												

Table S2.5. Principal component summary statistics. Eigenvalues of principal components and percentage of variance associated with each (obtained by applying principal components analysis to the risk category outputs from the 12 frameworks for the 10,000 simulated species).

	Eigenvalue	% Total variance	Cumulative Eigenvalue	Cumulative variance
PC1	1.95	16.23	1.95	16.23
PC2	1.56	13.03	3.51	29.26
PC3	1.33	11.11	4.84	40.37
PC4	1.28	10.69	6.21	51.06
PC5	0.97	8.05	7.09	59.11
PC6	0.90	7.48	7.99	66.59
PC7	0.87	7.27	8.86	73.86
PC8	0.83	6.93	9.69	80.79
PC9	0.71	5.89	10.40	86.68
PC10	0.66	5.47	11.06	92.50
PC11	0.49	4.06	11.55	96.20
PC12	0.45	3.79	12.00	100

Figure S3.1. Stacked species richness for a) birds and b) butterflies for current and projected future distributions under each of the three climate scenarios considered.

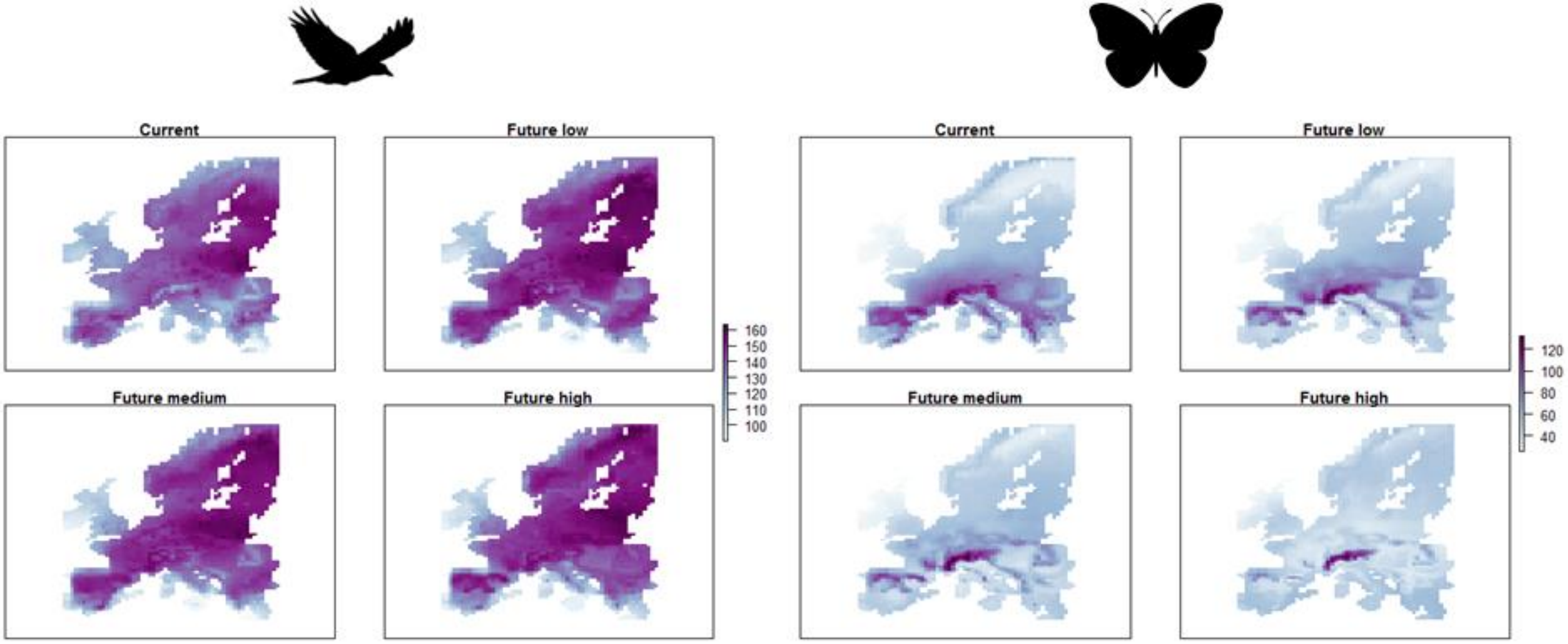


Figure S3.2. Drivers of spatial priority change across Europe, with change in priority rank of cells caused primarily by existing species remaining in the cell (refugia - blue) or new species occupying the cell (colonisation - red). Priority change calculated between the current and future high (RCP 8.5) climate based prioritizations for both birds and butterflies.

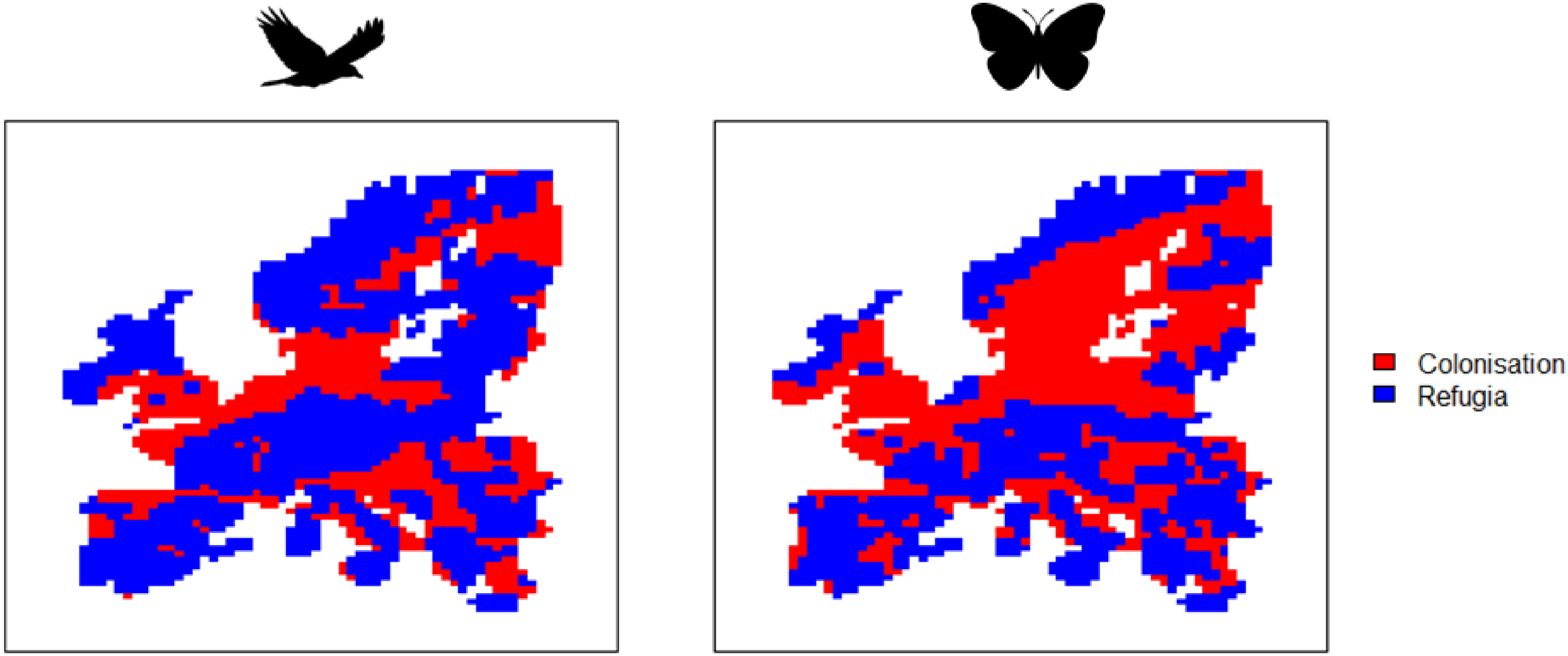


Figure S3.3. Stacked species richness across Europe for current distributions of a) high risk birds, b) high opportunity birds, c) high risk butterflies, d) high opportunity butterflies.

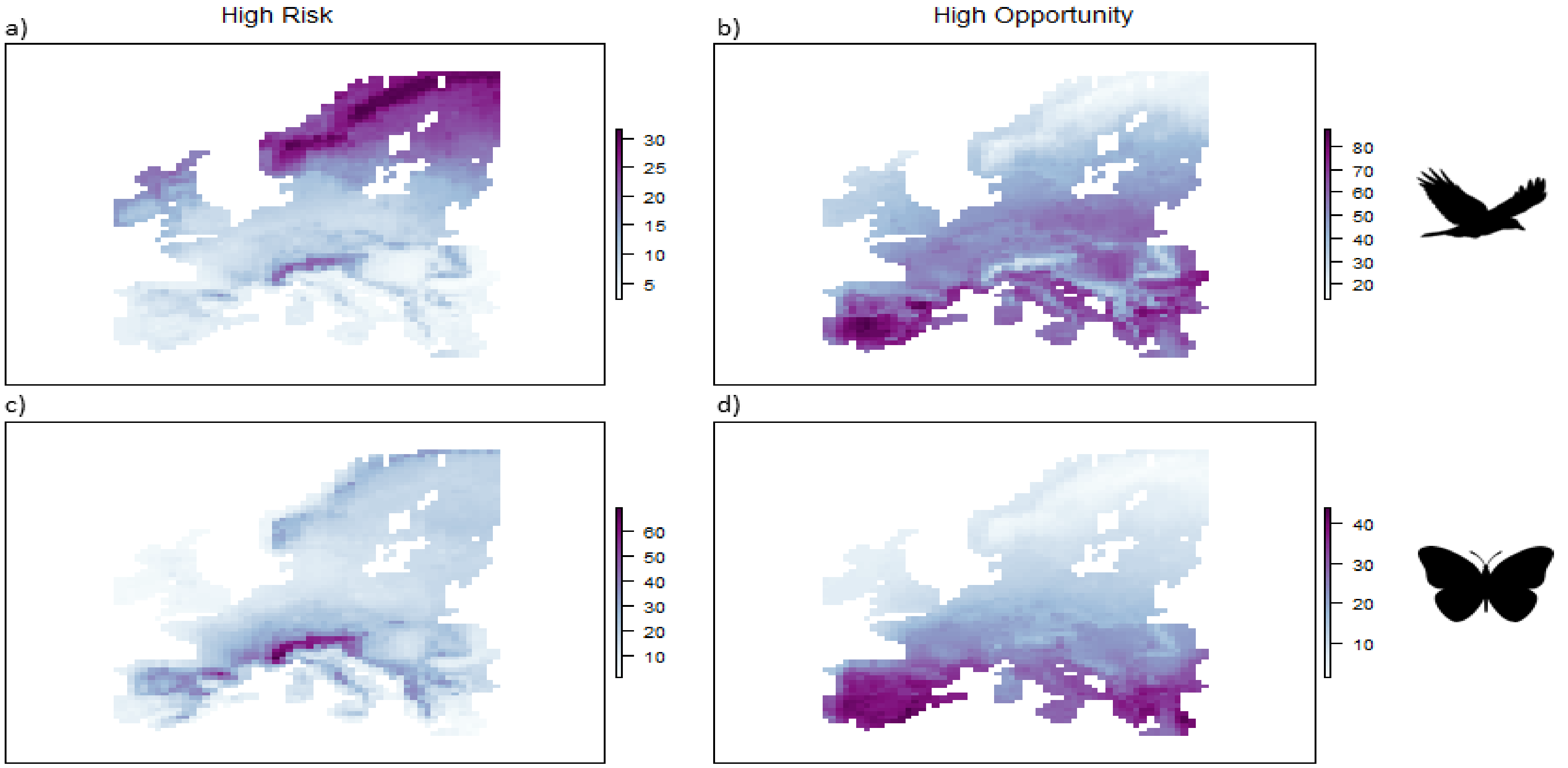


Figure S3.4. Stacked species richness across Europe for high risk species of bird and butterflies given projected range changes under future climate scenarios.

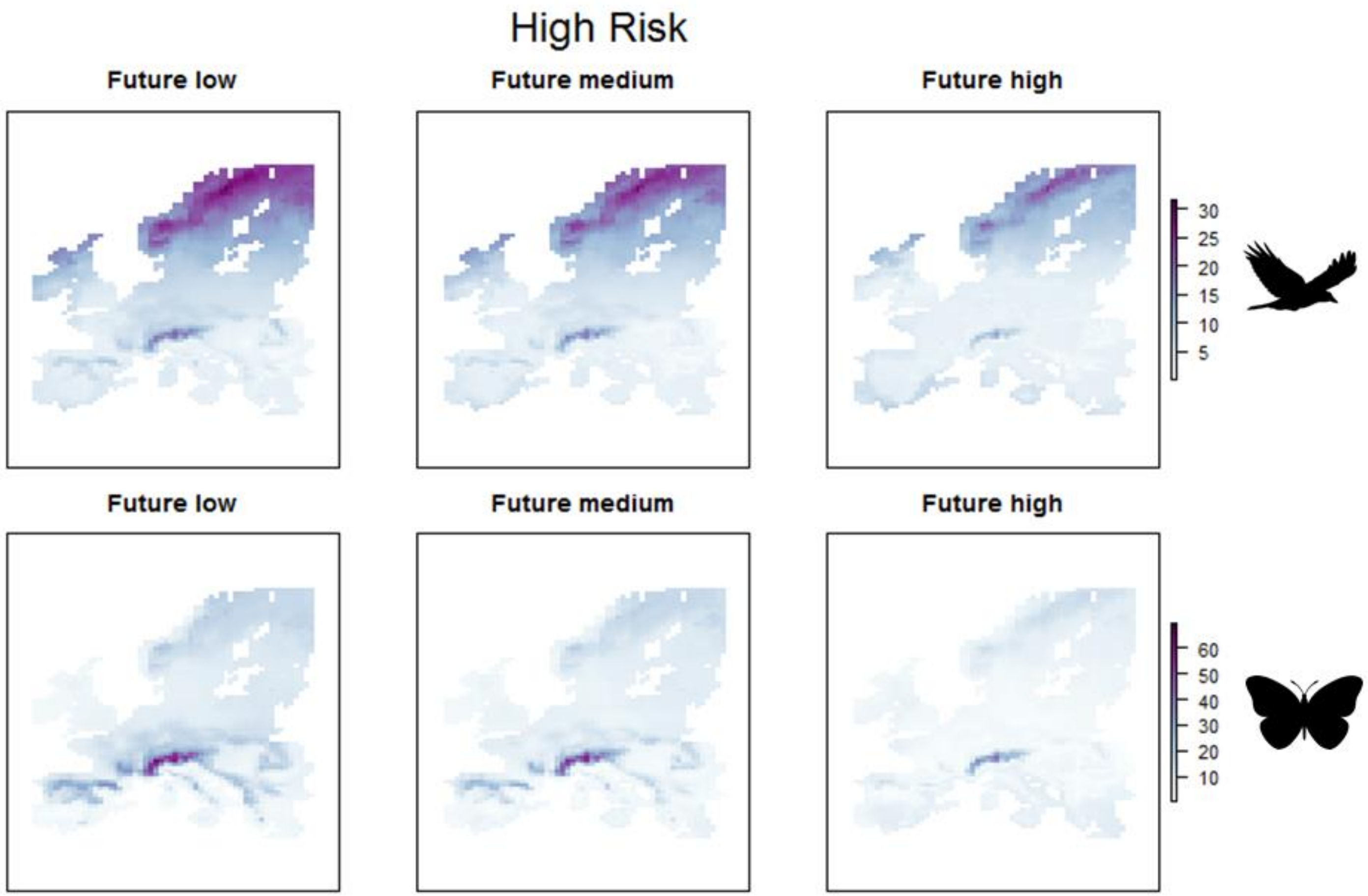
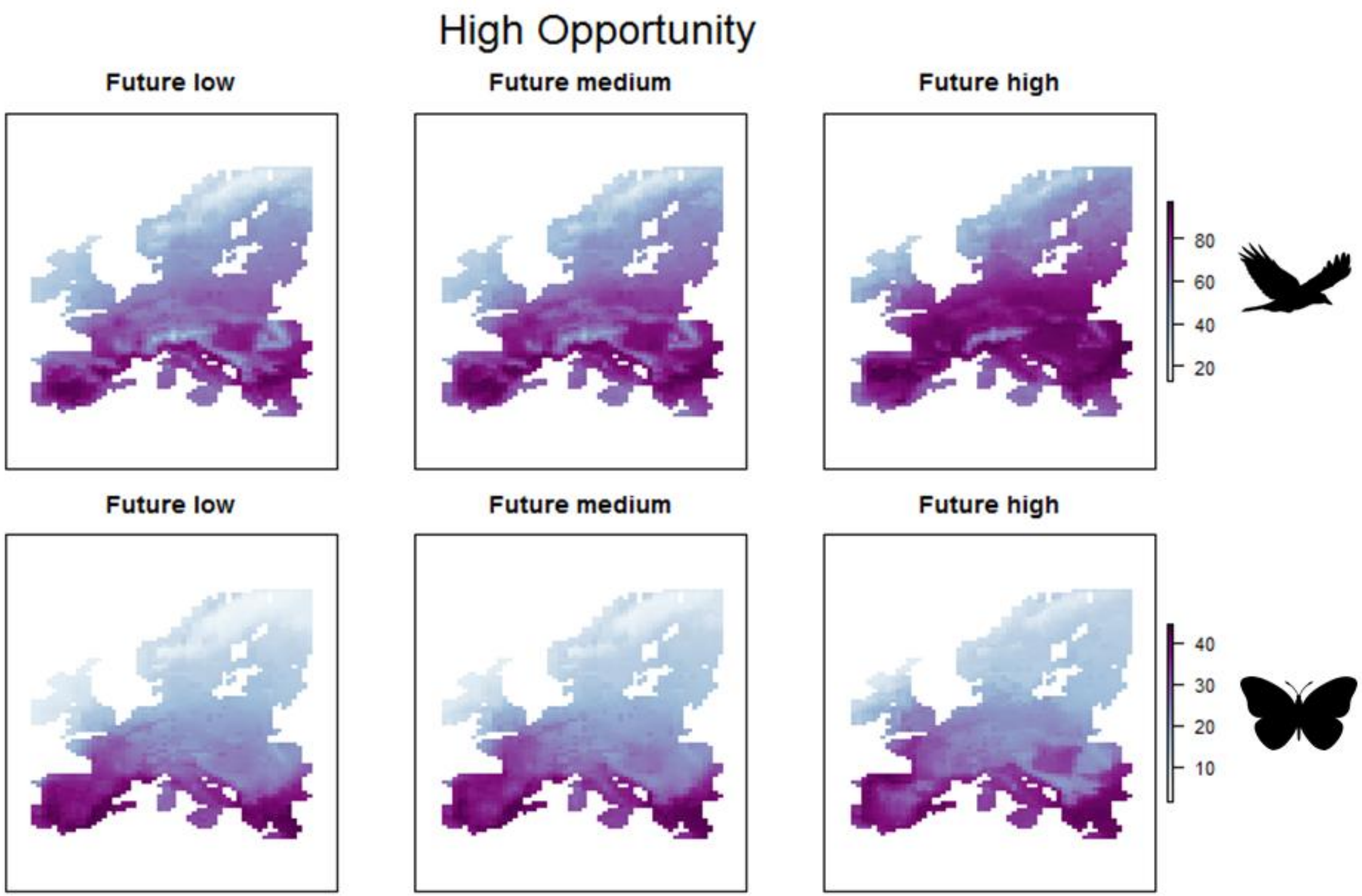


Figure S3.5. Stacked species richness across Europe for high opportunity species of bird and butterflies given projected range changes under future climate scenarios.



Appendix

Table S3.1. Full climate vulnerability assessment results for birds and butterflies. Overall climate risk score category are presented for each of the three RCP climate scenarios considered.

Scientific name	Common Name	Climate Risk Category		
Birds		**RCP 2.6**	**RCP 4.5**	**RCP 8.5**
Accipiter brevipes	Levant Sparrowhawk	Medium opportunity	High opportunity	Risks and opportunity
Accipiter gentilis	Northern Goshawk	Limited impact	Medium risk	Medium risk
Accipiter nisus	Eurasian Sparrowhawk	Limited impact	Limited impact	Medium risk
Acrocephalus agricola	Paddyfield Warbler	Medium risk	Medium risk	Medium risk
Acrocephalus arundinaceus	Great Reed-warbler	High opportunity	High opportunity	High opportunity
Acrocephalus dumetorum	Blyth's Reed-warbler	Medium opportunity	High opportunity	Medium opportunity
Acrocephalus melanopogon	Moustached Warbler	High opportunity	High opportunity	High opportunity
Acrocephalus paludicola	Aquatic Warbler	High risk	High risk	High risk
Acrocephalus palustris	Marsh Warbler	High opportunity	High opportunity	High opportunity
Acrocephalus schoenobaenus	Sedge Warbler	Medium opportunity	Medium opportunity	Medium opportunity
Acrocephalus scirpaceus	Eurasian Reed-warbler	High opportunity	High opportunity	Risks and opportunity
Actitis hypoleucos	Common Sandpiper	Medium opportunity	Medium opportunity	Medium opportunity
Aegithalos caudatus	Long-tailed Tit	Medium opportunity	Medium opportunity	Risks and opportunity
Aegolius funereus	Boreal Owl	High risk	High risk	High risk
Aegypius monachus	Cinereous Vulture	Medium risk	Medium risk	Medium risk
Alauda arvensis	Eurasian Skylark	High opportunity	High opportunity	Medium opportunity
Alca torda	Razorbill	High risk	High risk	High risk
Alcedo atthis	Common Kingfisher	High opportunity	High opportunity	High opportunity
Alectoris barbara	Barbary Partridge	High opportunity	High opportunity	High opportunity
Alectoris chukar	Chukar	Medium opportunity	Medium opportunity	Medium opportunity
Alectoris graeca	Rock Partridge	Medium opportunity	Medium risk	High risk
Alectoris rufa	Red-legged Partridge	High opportunity	High opportunity	Medium opportunity
Anas acuta	Northern Pintail	High risk	High risk	Medium risk
Anas crecca	Common Teal	High risk	High risk	High risk
Anas platyrhynchos	Mallard	High opportunity	High opportunity	High opportunity
Anser anser	Greylag Goose	High opportunity	High opportunity	Medium opportunity
Anser brachyrhynchus	Pink-footed Goose	Medium risk	Medium risk	Medium risk
Anser erythropus	Lesser White-fronted Goose	High risk	High risk	High risk
Anser fabalis	Bean Goose	High risk	High risk	High risk
Anthus campestris	Tawny Pipit	Medium opportunity	Medium risk	High risk
Anthus cervinus	Red-throated Pipit	Medium risk	Medium risk	Medium risk
Anthus petrosus	Rock Pipit	High opportunity	High opportunity	Medium opportunity
Anthus pratensis	Meadow Pipit	Medium risk	Medium risk	Medium risk
Anthus trivialis	Tree Pipit	Medium risk	High risk	High risk
Apus apus	Common Swift	High opportunity	High opportunity	High opportunity
Apus caffer	White-rumped Swift	Medium risk	Medium risk	Medium risk
Apus pallidus	Pallid Swift	High opportunity	High opportunity	High opportunity

Appendix

Aquila chrysaetos	Golden Eagle	Medium risk	Medium risk	Medium risk
Aquila heliaca	Eastern Imperial Eagle	High opportunity	High opportunity	High opportunity
Ardea alba	Great White Egret	High opportunity	Medium opportunity	Medium opportunity
Ardea cinerea	Grey Heron	High opportunity	High opportunity	High opportunity
Ardea purpurea	Purple Heron	Medium opportunity	Medium opportunity	Medium opportunity
Ardeola ralloides	Squacco Heron	Medium opportunity	Medium opportunity	Medium opportunity
Arenaria interpres	Ruddy Turnstone	Medium opportunity	Medium opportunity	Risks and opportunity
Asio flammeus	Short-eared Owl	Medium opportunity	Limited impact	Medium risk
Asio otus	Northern Long-eared Owl	High opportunity	High opportunity	Medium opportunity
Athene noctua	Little Owl	Medium opportunity	Medium opportunity	Medium opportunity
Aythya ferina	Common Pochard	High opportunity	High opportunity	High opportunity
Aythya fuligula	Tufted Duck	High risk	High risk	High risk
Aythya marila	Greater Scaup	High risk	High risk	High risk
Aythya nyroca	Ferruginous Duck	High opportunity	High opportunity	High opportunity
Bombycilla garrulus	Bohemian Waxwing	Medium risk	Medium risk	Medium risk
Bonasa bonasia	Hazel Grouse	High risk	High risk	High risk
Botaurus stellaris	Eurasian Bittern	High opportunity	High opportunity	High opportunity
Branta bernicla	Brent Goose	Medium risk	Medium risk	Medium risk
Branta canadensis	Canada Goose	Medium opportunity	Medium opportunity	High risk
Branta leucopsis	Barnacle Goose	Medium risk	Medium risk	Medium risk
Bubo bubo	Eurasian Eagle-owl	Medium opportunity	Medium opportunity	High opportunity
Bubo scandiacus	Snowy Owl	High risk	High risk	High risk
Bubulcus ibis	Cattle Egret	Medium opportunity	Medium opportunity	Medium opportunity
Bucanetes githagineus	Trumpeter Finch	Medium opportunity	Medium opportunity	Medium opportunity
Bucephala clangula	Common Goldeneye	Limited impact	Limited impact	Medium risk
Burhinus oedicnemus	Eurasian Thick-knee	High opportunity	High opportunity	High opportunity
Buteo buteo	Eurasian Buzzard	High opportunity	High opportunity	High opportunity
Buteo lagopus	Rough-legged Buzzard	Medium risk	Medium risk	High risk
Buteo rufinus	Long-legged Buzzard	High opportunity	High opportunity	High opportunity
Calandrella brachydactyla	Greater Short-toed Lark	High opportunity	High opportunity	High opportunity
Calandrella rufescens	Lesser Short-toed Lark	High opportunity	High opportunity	High opportunity
Calcarius lapponicus	Lapland Longspur	Medium risk	Medium risk	Medium risk
Calidris alpina	Dunlin	Medium risk	Medium risk	Medium risk
Calidris falcinellus	Broad-billed Sandpiper	Risks and opportunity	Medium risk	Medium risk
Calidris maritima	Purple Sandpiper	Medium risk	Medium risk	Medium risk
Calidris minuta	Little Stint	High risk	High risk	High risk
Calidris pugnax	Ruff	Medium risk	Medium risk	Medium risk
Calidris temminckii	Temminck's Stint	High risk	High risk	High risk
Calonectris diomedea	Scopoli's Shearwater	High risk	High risk	Medium risk
Caprimulgus europaeus	European Nightjar	Medium risk	Medium risk	Medium risk
Caprimulgus ruficollis	Red-necked Nightjar	High opportunity	High opportunity	High opportunity
Carduelis cannabina	Eurasian Linnet	High opportunity	High opportunity	Medium opportunity
Carduelis carduelis	European Goldfinch	High opportunity	High opportunity	High opportunity
Carduelis chloris	European Greenfinch	High opportunity	High opportunity	High opportunity
Carduelis citrinella	Alpine Citril Finch	High risk	High risk	High risk
Carduelis flammea	Common Redpoll	High risk	High risk	High risk
Carduelis flavirostris	Twite	High risk	High risk	High risk

Appendix

Carduelis spinus	Eurasian Siskin	Limited impact	Medium risk	Medium risk
Carpodacus erythrinus	Common Rosefinch	Medium risk	Medium risk	Medium risk
Catharacta skua	Great Skua	Medium risk	Medium risk	Risks and opportunity
Cepphus grylle	Black Guillemot	Risks and opportunity	Medium opportunity	Medium opportunity
Certhia brachydactyla	Short-toed Treecreeper	Medium opportunity	Medium opportunity	Medium risk
Certhia familiaris	Eurasian Treecreeper	Medium risk	Medium risk	Medium opportunity
Cettia cetti	Cetti's Warbler	High opportunity	High opportunity	High opportunity
Charadrius alexandrinus	Kentish Plover	High opportunity	High opportunity	Medium opportunity
Charadrius dubius	Little Ringed Plover	High opportunity	High opportunity	High opportunity
Charadrius hiaticula	Common Ringed Plover	Medium risk	Medium risk	Medium risk
Chersophilus duponti	Dupont's Lark	Risks and opportunity	High risk	High risk
Chlidonias hybrida	Whiskered Tern	High opportunity	High opportunity	High opportunity
Chlidonias leucopterus	White-winged Tern	High opportunity	High opportunity	High opportunity
Chlidonias niger	Black Tern	Medium opportunity	Medium opportunity	Medium opportunity
Ciconia ciconia	White Stork	High opportunity	High opportunity	High opportunity
Ciconia nigra	Black Stork	High opportunity	High opportunity	High opportunity
Cinclus cinclus	White-throated Dipper	High risk	High risk	High risk
Circaetus gallicus	Short-toed Snake-eagle	High opportunity	High opportunity	Medium risk
Circus aeruginosus	Western Marsh-harrier	High opportunity	High opportunity	High opportunity
Circus cyaneus	Hen Harrier	High risk	High risk	High risk
Circus pygargus	Montagu's Harrier	High opportunity	High opportunity	High opportunity
Cisticola juncidis	Zitting Cisticola	High opportunity	High opportunity	High opportunity
Clamator glandarius	Great Spotted Cuckoo	High opportunity	High opportunity	High opportunity
Clanga clanga	Greater Spotted Eagle	High risk	High risk	High risk
Clanga pomarina	Lesser Spotted Eagle	Medium risk	Medium risk	Medium risk
Clangula hyemalis	Long-tailed Duck	High risk	High risk	High risk
Coccothraustes coccothraustes	Hawfinch	Limited impact	Limited impact	Medium opportunity
Columba livia	Rock Dove	Medium opportunity	High opportunity	High opportunity
Columba oenas	Stock Dove	High opportunity	High opportunity	High opportunity
Columba palumbus	Common Woodpigeon	Limited impact	Limited impact	Limited impact
Coracias garrulus	European Roller	High opportunity	High opportunity	High opportunity
Corvus corax	Common Raven	Limited impact	Limited impact	Medium opportunity
Corvus corone	Carrion Crow	Medium opportunity	Medium opportunity	Medium opportunity
Corvus frugilegus	Rook	Risks and opportunity	Risks and opportunity	Medium risk
Corvus monedula	Eurasian Jackdaw	High opportunity	High opportunity	High opportunity
Coturnix coturnix	Common Quail	High opportunity	High opportunity	High opportunity
Crex crex	Corncrake	Medium opportunity	Medium opportunity	Risks and opportunity
Cuculus canorus	Common Cuckoo	Medium opportunity	Medium opportunity	Medium opportunity
Cuculus saturatus	Oriental Cuckoo	Medium risk	Medium risk	Medium risk
Cyanopica cyanus	Azure-winged Magpie	Limited impact	High opportunity	High opportunity
Cygnus cygnus	Whooper Swan	Medium risk	Medium risk	Medium risk
Cygnus olor	Mute Swan	Medium opportunity	Medium opportunity	Medium risk
Delichon urbicum	Northern House-martin	Medium opportunity	Medium opportunity	Risks and opportunity
Dendrocopos leucotos	White-backed Woodpecker	Medium risk	Medium risk	Medium risk

Dendrocopos major	Great Spotted Woodpecker	Medium risk	Medium risk	Medium risk
Dendrocopos syriacus	Syrian Woodpecker	High opportunity	High opportunity	High opportunity
Dryobates minor	Lesser Spotted Woodpecker	Limited impact	Limited impact	Medium risk
Dryocopus martius	Black Woodpecker	Limited impact	Medium risk	Medium risk
Egretta garzetta	Little Egret	Medium opportunity	Medium opportunity	Medium opportunity
Elanus caeruleus	Black-winged Kite	High opportunity	High opportunity	High opportunity
Emberiza aureola	Yellow-breasted Bunting	High risk	High risk	High risk
Emberiza caesia	Cretzschmar's Bunting	High opportunity	High opportunity	High opportunity
Emberiza cia	Rock Bunting	Limited impact	Medium risk	Medium risk
Emberiza cineracea	Cinereous Bunting	Medium opportunity	Medium opportunity	Medium opportunity
Emberiza cirlus	Cirl Bunting	High opportunity	High opportunity	High opportunity
Emberiza citrinella	Yellowhammer	Medium risk	Medium risk	High risk
Emberiza hortulana	Ortolan Bunting	High opportunity	High opportunity	Risks and opportunity
Emberiza melanocephala	Black-headed Bunting	High opportunity	High opportunity	Risks and opportunity
Emberiza pusilla	Little Bunting	High risk	High risk	High risk
Emberiza rustica	Rustic Bunting	Medium risk	High risk	High risk
Emberiza schoeniclus	Reed Bunting	High opportunity	High opportunity	High opportunity
Eremophila alpestris	Horned Lark	High risk	High risk	High risk
Erithacus rubecula	European Robin	Medium risk	Medium risk	Medium risk
Erythropygia galactotes	Rufous-tailed Scrub-robin	High opportunity	High opportunity	High opportunity
Eudromias morinellus	Eurasian Dotterel	Medium risk	Medium risk	Medium risk
Falco biarmicus	Lanner Falcon	High risk	High risk	High risk
Falco cherrug	Saker Falcon	High opportunity	High opportunity	High opportunity
Falco columbarius	Merlin	Medium risk	Medium risk	Medium risk
Falco eleonorae	Eleonora's Falcon	High opportunity	High opportunity	High opportunity
Falco naumanni	Lesser Kestrel	Medium opportunity	Medium opportunity	Medium opportunity
Falco peregrinus	Peregrine Falcon	Limited impact	Limited impact	Limited impact
Falco rusticolus	Gyrfalcon	High risk	High risk	High risk
Falco subbuteo	Eurasian Hobby	Medium opportunity	Medium opportunity	High opportunity
Falco tinnunculus	Common Kestrel	High opportunity	High opportunity	High opportunity
Falco vespertinus	Red-footed Falcon	High opportunity	High opportunity	High opportunity
Ficedula albicollis	Collared Flycatcher	Medium risk	Medium risk	Medium risk
Ficedula hypoleuca	European Pied Flycatcher	Medium risk	Medium risk	Medium risk
Ficedula parva	Red-breasted Flycatcher	Medium risk	Medium risk	Medium risk
Fratercula arctica	Atlantic Puffin	High risk	High risk	High risk
Fringilla coelebs	Eurasian Chaffinch	Medium opportunity	Medium opportunity	Medium opportunity
Fringilla montifringilla	Brambling	Medium risk	Medium risk	Medium risk
Fulica atra	Common Coot	High opportunity	High opportunity	High opportunity
Fulmarus glacialis	Northern Fulmar	High risk	High risk	High risk
Galerida cristata	Crested Lark	High opportunity	High opportunity	High opportunity
Galerida theklae	Thekla Lark	High opportunity	High opportunity	Medium opportunity
Gallinago gallinago	Common Snipe	Medium risk	Medium risk	Medium risk
Gallinago media	Great Snipe	High risk	High risk	High risk
Gallinula chloropus	Common Moorhen	Medium opportunity	Medium opportunity	Risks and opportunity
Garrulus glandarius	Eurasian Jay	Limited impact	Medium opportunity	High opportunity
Gavia arctica	Arctic Loon	Medium risk	Medium risk	Medium risk
Gavia immer	Common Loon	High risk	High risk	High risk
Gavia stellata	Red-throated Loon	Medium risk	Medium risk	Medium risk

Gelochelidon nilotica	Common Gull-billed Tern	High opportunity	High opportunity	High opportunity
Glareola nordmanni	Black-winged Pratincole	Medium opportunity	Medium opportunity	Risks and opportunity
Glareola pratincola	Collared Pratincole	High opportunity	High opportunity	High opportunity
Glaucidium passerinum	Eurasian Pygmy-owl	Medium risk	Medium risk	Medium risk
Grus grus	Common Crane	High opportunity	Medium opportunity	Medium risk
Gypaetus barbatus	Bearded Vulture	High risk	High risk	High risk
Gyps fulvus	Griffon Vulture	Limited impact	Limited impact	Medium risk
Haematopus ostralegus	Eurasian Oystercatcher	Risks and opportunity	Risks and opportunity	Risks and opportunity
Haliaeetus albicilla	White-tailed Sea-eagle	High opportunity	High opportunity	High opportunity
Hieraaetus pennatus	Booted Eagle	Limited impact	Limited impact	Medium risk
Himantopus himantopus	Black-winged Stilt	High opportunity	High opportunity	High opportunity
Hippolais icterina	Icterine Warbler	High opportunity	Risks and opportunity	Risks and opportunity
Hippolais olivetorum	Olive-tree Warbler	High opportunity	High opportunity	High opportunity
Hippolais pallida	Eastern Olivaceous Warbler	Medium opportunity	Medium opportunity	Medium opportunity
Hippolais polyglotta	Melodious Warbler	Medium opportunity	Risks and opportunity	Medium risk
Hirundo daurica	Red-rumped Swallow	High opportunity	High opportunity	Medium opportunity
Hirundo rupestris	Eurasian Crag-martin	Limited impact	Medium risk	Medium risk
Hirundo rustica	Barn Swallow	High opportunity	High opportunity	Medium opportunity
Hydrobates castro	Band-rumped Storm-petrel	High opportunity	High opportunity	High opportunity
Hydrobates leucorhous	Leach's Storm-petrel	Medium risk	Medium risk	Medium risk
Hydrobates pelagicus	European Storm-petrel	Medium opportunity	Medium opportunity	Medium opportunity
Hydrocoloeus minutus	Little Gull	Medium opportunity	Risks and opportunity	Risks and opportunity
Hydroprogne caspia	Caspian Tern	Medium risk	Medium risk	Risks and opportunity
Ixobrychus minutus	Common Little Bittern	High opportunity	High opportunity	High opportunity
Jynx torquilla	Eurasian Wryneck	Limited impact	Limited impact	Medium risk
Lagopus lagopus	Willow Grouse	High risk	High risk	High risk
Lagopus muta	Rock Ptarmigan	High risk	High risk	High risk
Lanius collurio	Red-backed Shrike	Medium risk	Medium risk	Medium risk
Lanius minor	Lesser Grey Shrike	Medium opportunity	Medium opportunity	Medium risk
Lanius nubicus	Masked Shrike	High opportunity	High opportunity	High opportunity
Lanius senator	Woodchat Shrike	High opportunity	High opportunity	Medium opportunity
Larus argentatus	European Herring Gull	High risk	High risk	High risk
Larus audouinii	Audouin's Gull	Medium risk	Medium risk	Medium risk
Larus cachinnans	Caspian Gull	High opportunity	High opportunity	High opportunity
Larus canus	Mew Gull	High risk	High risk	High risk
Larus fuscus	Lesser Black-backed Gull	Medium risk	Medium risk	Medium risk
Larus genei	Slender-billed Gull	High opportunity	High opportunity	High opportunity
Larus marinus	Great Black-backed Gull	Risks and opportunity	Medium risk	High risk
Larus melanocephalus	Mediterranean Gull	Medium opportunity	Medium opportunity	Risks and opportunity
Larus ridibundus	Black-headed Gull	Medium opportunity	Medium opportunity	Medium opportunity
Leiopicus medius	Middle Spotted Woodpecker	Medium risk	Medium risk	Medium risk
Limosa lapponica	Bar-tailed Godwit	Medium risk	Medium risk	Medium risk
Limosa limosa	Black-tailed Godwit	Medium opportunity	Medium opportunity	Medium opportunity

Locustella fluviatilis	Eurasian River Warbler	High opportunity	High opportunity	Medium opportunity
Locustella luscinioides	Savi's Warbler	Medium opportunity	Medium opportunity	Medium opportunity
Locustella naevia	Common Grasshopper-warbler	Risks and opportunity	Medium risk	High risk
Loxia curvirostra	Red Crossbill	Limited impact	Medium risk	Medium risk
Loxia leucoptera	White-winged Crossbill	Medium opportunity	Medium risk	Medium risk
Loxia pytyopsittacus	Parrot Crossbill	Limited impact	Medium risk	Medium risk
Lullula arborea	Wood Lark	Medium risk	Medium opportunity	Medium opportunity
Luscinia luscinia	Thrush Nightingale	Medium opportunity	Medium opportunity	Risks and opportunity
Luscinia megarhynchos	Common Nightingale	High opportunity	High opportunity	High opportunity
Luscinia svecica	Bluethroat	Medium opportunity	Medium risk	Medium risk
Lymnocryptes minimus	Jack Snipe	High risk	High risk	High risk
Lyrurus tetrix	Black Grouse	High risk	High risk	High risk
Mareca penelope	Eurasian Wigeon	Medium risk	Medium risk	Medium risk
Mareca strepera	Gadwall	High opportunity	High opportunity	High opportunity
Marmaronetta angustirostris	Marbled Teal	Medium opportunity	Medium opportunity	Medium opportunity
Melanitta fusca	Velvet Scoter	High risk	High risk	High risk
Melanitta nigra	Common Scoter	Medium risk	Medium risk	Medium risk
Melanocorypha calandra	Calandra Lark	High opportunity	High opportunity	High opportunity
Mergellus albellus	Smew	Medium risk	Medium risk	Medium risk
Mergus merganser	Goosander	Limited impact	Limited impact	Medium risk
Mergus serrator	Red-breasted Merganser	High risk	High risk	High risk
Merops apiaster	European Bee-eater	High opportunity	High opportunity	High opportunity
Microcarbo pygmaeus	Pygmy Cormorant	High opportunity	High opportunity	High opportunity
Miliaria calandra	Corn Bunting	High opportunity	High opportunity	High opportunity
Milvus migrans	Black Kite	High opportunity	High opportunity	High opportunity
Milvus milvus	Red Kite	Medium opportunity	Medium opportunity	High opportunity
Monticola saxatilis	Rufous-tailed Rock-thrush	High risk	High risk	High risk
Monticola solitarius	Blue Rock-thrush	High opportunity	Risks and opportunity	Risks and opportunity
Montifringilla nivalis	White-winged Snowfinch	High risk	High risk	High risk
Morus bassanus	Northern Gannet	High opportunity	High opportunity	High opportunity
Motacilla alba	White Wagtail	High opportunity	High opportunity	High opportunity
Motacilla cinerea	Grey Wagtail	Medium risk	Medium risk	Medium risk
Motacilla citreola	Citrine Wagtail	High risk	High risk	High risk
Motacilla flava	Yellow Wagtail	High opportunity	High opportunity	High opportunity
Muscicapa striata	Spotted Flycatcher	Limited impact	Medium risk	Medium risk
Neophron percnopterus	Egyptian Vulture	Medium opportunity	Medium risk	High risk
Netta rufina	Red-crested Pochard	High opportunity	High opportunity	High opportunity
Nucifraga caryocatactes	Spotted Nutcracker	Medium risk	Medium risk	Medium risk
Numenius arquata	Eurasian Curlew	High risk	High risk	High risk
Numenius phaeopus	Whimbrel	Medium risk	Medium risk	Medium risk
Nycticorax nycticorax	Black-crowned Night-heron	Medium opportunity	Medium opportunity	Medium opportunity
Oenanthe hispanica	Black-eared Wheatear	Medium opportunity	Medium opportunity	Medium opportunity
Oenanthe isabellina	Isabelline Wheatear	High opportunity	High opportunity	High opportunity
Oenanthe leucura	Black Wheatear	High risk	High risk	High risk
Oenanthe oenanthe	Northern Wheatear	Limited impact	Medium opportunity	Medium opportunity
Oenanthe pleschanka	Pied Wheatear	High opportunity	High opportunity	High opportunity
Oriolus oriolus	Eurasian Golden Oriole	High opportunity	High opportunity	High opportunity

Otis tarda	Great Bustard	High opportunity	High opportunity	High opportunity
Otus scops	Eurasian Scops-owl	High opportunity	High opportunity	High opportunity
Oxyura leucocephala	White-headed Duck	High opportunity	High opportunity	High opportunity
Pandion haliaetus	Osprey	High opportunity	High opportunity	High opportunity
Panurus biarmicus	Bearded Parrotbill	Medium opportunity	Medium opportunity	Medium opportunity
Parus ater	Coal Tit	Limited impact	Limited impact	Medium risk
Parus caeruleus	Blue Tit	High opportunity	High opportunity	High opportunity
Parus cinctus	Siberian Tit	Medium risk	Medium risk	Medium risk
Parus cristatus	Crested Tit	High risk	High risk	High risk
Parus lugubris	Sombre Tit	High opportunity	Risks and opportunity	Medium risk
Parus major	Great Tit	High opportunity	High opportunity	High opportunity
Parus montanus	Willow Tit	Limited impact	Medium risk	Medium risk
Parus palustris	Marsh Tit	Medium risk	High risk	High risk
Passer domesticus	House Sparrow	High opportunity	High opportunity	Limited impact
Passer hispaniolensis	Spanish Sparrow	High opportunity	High opportunity	High opportunity
Passer montanus	Eurasian Tree Sparrow	High opportunity	High opportunity	Risks and opportunity
Pelecanus crispus	Dalmatian Pelican	High opportunity	High opportunity	High opportunity
Pelecanus onocrotalus	Great White Pelican	Risks and opportunity	Risks and opportunity	Risks and opportunity
Perdix perdix	Grey Partridge	Medium risk	Risks and opportunity	Medium risk
Perisoreus infaustus	Siberian Jay	Limited impact	Medium risk	Medium risk
Pernis apivorus	European Honey-buzzard	Limited impact	Limited impact	Limited impact
Petronia petronia	Rock Sparrow	High opportunity	High opportunity	High opportunity
Phalacrocorax aristotelis	European Shag	Medium risk	Risks and opportunity	Risks and opportunity
Phalacrocorax carbo	Great Cormorant	Risks and opportunity	Medium opportunity	Medium opportunity
Phalaropus lobatus	Red-necked Phalarope	Medium risk	Medium risk	Medium risk
Phasianus colchicus	Common Pheasant	High opportunity	High opportunity	High opportunity
Phoenicurus ochruros	Black Redstart	Limited impact	Limited impact	Medium risk
Phoenicurus phoenicurus	Common Redstart	Limited impact	Medium risk	Medium risk
Phylloscopus bonelli	Bonelli's Warbler	Limited impact	Medium risk	Medium risk
Phylloscopus borealis	Arctic Warbler	High risk	High risk	High risk
Phylloscopus collybita	Common Chiffchaff	Medium risk	Medium risk	Medium risk
Phylloscopus sibilatrix	Wood Warbler	High risk	High risk	High risk
Phylloscopus trochilus	Willow Warbler	Limited impact	Limited impact	Medium risk
Pica pica	Black-billed Magpie	Medium opportunity	Limited impact	Limited impact
Picoides tridactylus	Three-toed Woodpecker	Medium risk	Medium risk	Medium risk
Picus canus	Grey-faced Woodpecker	Medium opportunity	Risks and opportunity	Medium risk
Picus viridis	Eurasian Green Woodpecker	Risks and opportunity	Medium risk	High risk
Pinicola enucleator	Pine Grosbeak	High risk	High risk	High risk
Platalea leucorodia	Eurasian Spoonbill	Medium opportunity	Medium opportunity	Medium opportunity
Plectrophenax nivalis	Snow Bunting	Medium risk	Medium risk	Medium risk
Plegadis falcinellus	Glossy Ibis	High opportunity	High opportunity	High opportunity
Pluvialis apricaria	Eurasian Golden Plover	Medium risk	Medium risk	Medium risk
Podiceps auritus	Horned Grebe	Risks and opportunity	Medium risk	Medium risk
Podiceps cristatus	Great Crested Grebe	High opportunity	High opportunity	High opportunity
Podiceps grisegena	Red-necked Grebe	Risks and opportunity	Risks and opportunity	Risks and opportunity
Podiceps nigricollis	Black-necked Grebe	Medium opportunity	Medium opportunity	Medium opportunity
Porphyrio porphyrio	Purple Swamphen	High opportunity	High opportunity	High opportunity

Appendix

Porzana porzana	Spotted Crake	High opportunity	High opportunity	High opportunity
Prunella collaris	Alpine Accentor	High risk	High risk	High risk
Prunella modularis	Hedge Accentor	Medium risk	High risk	High risk
Pterocles alchata	Pin-tailed Sandgrouse	High opportunity	High opportunity	High opportunity
Pterocles orientalis	Black-bellied Sandgrouse	High opportunity	Risks and opportunity	Medium risk
Puffinus puffinus	Manx Shearwater	Medium risk	Medium risk	High risk
Puffinus yelkouan	Yelkouan Shearwater	Medium risk	Medium risk	Risks and opportunity
Pyrrhocorax graculus	Yellow-billed Chough	High risk	High risk	High risk
Pyrrhocorax pyrrhocorax	Red-billed Chough	High risk	High risk	Medium risk
Pyrrhula pyrrhula	Eurasian Bullfinch	Medium risk	Medium risk	High risk
Rallus aquaticus	Western Water Rail	High opportunity	High opportunity	High opportunity
Recurvirostra avosetta	Pied Avocet	High opportunity	High opportunity	High opportunity
Regulus ignicapilla	Firecrest	Limited impact	Medium risk	Medium risk
Regulus regulus	Goldcrest	Limited impact	Limited impact	Medium risk
Remiz pendulinus	Eurasian Penduline-tit	High opportunity	High opportunity	High opportunity
Riparia riparia	Sand Martin	High opportunity	High opportunity	High opportunity
Rissa tridactyla	Black-legged Kittiwake	High risk	High risk	High risk
Saxicola rubetra	Whinchat	Limited impact	Limited impact	Medium risk
Saxicola torquatus	Common Stonechat	High opportunity	High opportunity	Medium opportunity
Scolopax rusticola	Eurasian Woodcock	Limited impact	Limited impact	Medium risk
Serinus serinus	European Serin	Limited impact	High opportunity	High opportunity
Sitta europaea	Wood Nuthatch	Limited impact	Limited impact	Medium risk
Sitta neumayer	Western Rock-nuthatch	High opportunity	High opportunity	High opportunity
Sitta whiteheadi	Corsican Nuthatch	High risk	High risk	High risk
Somateria mollissima	Common Eider	High risk	Medium risk	Medium risk
Spatula clypeata	Northern Shoveler	High opportunity	High opportunity	High opportunity
Spatula querquedula	Garganey	Medium opportunity	Medium opportunity	Medium opportunity
Stercorarius longicaudus	Long-tailed Jaeger	Medium risk	Medium risk	Medium risk
Stercorarius parasiticus	Arctic Jaeger	High risk	High risk	High risk
Sterna dougallii	Roseate Tern	Medium risk	Medium risk	Medium risk
Sterna hirundo	Common Tern	Medium opportunity	Medium opportunity	Medium opportunity
Sterna paradisaea	Arctic Tern	Medium risk	Medium risk	Medium risk
Sternula albifrons	Little Tern	Medium opportunity	Medium opportunity	Medium opportunity
Streptopelia decaocto	Eurasian Collared-dove	High opportunity	High opportunity	High opportunity
Streptopelia turtur	European Turtle-dove	Medium opportunity	Medium opportunity	Medium opportunity
Strix aluco	Tawny Owl	Limited impact	Medium opportunity	Medium opportunity
Strix nebulosa	Great Grey Owl	Risks and opportunity	Risks and opportunity	Medium risk
Strix uralensis	Ural Owl	High risk	High risk	High risk
Sturnus roseus	Rosy Starling	Medium opportunity	Medium opportunity	Risks and opportunity
Sturnus unicolor	Spotless Starling	High opportunity	High opportunity	High opportunity
Sturnus vulgaris	Common Starling	Medium opportunity	Medium opportunity	Medium opportunity
Surnia ulula	Northern Hawk-owl	Limited impact	Limited impact	Medium risk
Sylvia atricapilla	Blackcap	High opportunity	High opportunity	High opportunity
Sylvia borin	Garden Warbler	Medium risk	High risk	High risk
Sylvia cantillans	Subalpine Warbler	High opportunity	High opportunity	High opportunity
Sylvia communis	Common Whitethroat	High opportunity	High opportunity	High opportunity
Sylvia conspicillata	Spectacled Warbler	Medium opportunity	Medium opportunity	Medium risk

Appendix

Sylvia curruca	Lesser Whitethroat	Medium opportunity	Medium opportunity	Limited impact
Sylvia hortensis	Orphean Warbler	High opportunity	High opportunity	High opportunity
Sylvia melanocephala	Sardinian Warbler	High opportunity	High opportunity	High opportunity
Sylvia nisoria	Barred Warbler	Medium opportunity	Medium opportunity	Medium opportunity
Sylvia rueppelli	Rueppell's Warbler	High risk	High risk	High risk
Sylvia sarda	Marmora's Warbler	High risk	High risk	Risks and opportunity
Sylvia undata	Dartford Warbler	Medium risk	High risk	High risk
Tachybaptus ruficollis	Little Grebe	High opportunity	High opportunity	High opportunity
Tachymarptis melba	Alpine Swift	Medium opportunity	Medium risk	Medium risk
Tadorna ferruginea	Ruddy Shelduck	High opportunity	High opportunity	High opportunity
Tadorna tadorna	Common Shelduck	High opportunity	High opportunity	High opportunity
Tetrao urogallus	Western Capercaillie	High risk	High risk	Medium risk
Tetrax tetrax	Little Bustard	Risks and opportunity	High risk	High risk
Thalasseus sandvicensis	Sandwich Tern	Medium opportunity	Medium opportunity	Risks and opportunity
Tichodroma muraria	Wallcreeper	High risk	High risk	High risk
Tringa erythropus	Spotted Redshank	Medium risk	Medium risk	Medium risk
Tringa glareola	Wood Sandpiper	Medium risk	Medium risk	Medium risk
Tringa nebularia	Common Greenshank	High opportunity	High opportunity	High opportunity
Tringa ochropus	Green Sandpiper	Medium opportunity	Limited impact	Medium risk
Tringa stagnatilis	Marsh Sandpiper	Medium opportunity	Medium opportunity	Medium opportunity
Tringa totanus	Common Redshank	Medium opportunity	Medium opportunity	Medium opportunity
Troglodytes troglodytes	Winter Wren	Medium risk	Medium risk	Medium risk
Turdus iliacus	Redwing	High risk	High risk	High risk
Turdus merula	Eurasian Blackbird	High opportunity	High opportunity	High opportunity
Turdus philomelos	Song Thrush	Medium risk	Medium risk	Medium risk
Turdus pilaris	Fieldfare	Limited impact	Limited impact	Medium risk
Turdus torquatus	Ring Ouzel	High risk	High risk	High risk
Turdus viscivorus	Mistle Thrush	Medium risk	Medium risk	Medium risk
Tyto alba	Common Barn-owl	High opportunity	High opportunity	High opportunity
Upupa epops	Common Hoopoe	High opportunity	High opportunity	High opportunity
Uria aalge	Common Murre	High risk	High risk	High risk
Uria lomvia	Thick-billed Murre	High risk	High risk	High risk
Vanellus vanellus	Northern Lapwing	High opportunity	High opportunity	High opportunity
Zapornia parva	Little Crake	High opportunity	High opportunity	High opportunity
Zapornia pusilla	Baillon's Crake	High opportunity	High opportunity	High opportunity

Appendix

Scientific name	Common Name	Climate Risk Category		
Butterflies		**RCP 2.6**	**RCP 4.5**	**RCP 8.5**
Aglais io	European Peacock	Risks and opportunity	Medium opportunity	High opportunity
Aglais urticae	Small tortoiseshell	Medium risk	Medium risk	High risk
Anthocharis cardamines	Orange Tip	Medium risk	Medium risk	Medium risk
Anthocharis damone	Eastern Orange Tip	High risk	High risk	High risk
Anthocharis euphenoides	Provence orange tip	High risk	High risk	High risk
Anthocharis gruneri	Gruner's Orange Tip	High risk	High risk	High risk
Apatura ilia	Lesser Purple Emperor	Medium risk	High risk	High risk
Apatura iris	Purple Emperor	Medium risk	High risk	High risk
Apatura metis	Freyer's Purple Emperor	High opportunity	High opportunity	High opportunity
Aphantopus hyperantus	Ringlet	Risks and opportunity	Medium opportunity	Risks and opportunity
Aporia crataegi	Black-veined White	Medium risk	High risk	High risk
Araschnia levana	Map Butterfly	Medium risk	Medium risk	High risk
Archon apollinus	False Apollo	High opportunity	High opportunity	High opportunity
Arethusana arethusa	False grayling	High risk	High risk	High risk
Argynnis adippe	High Brown Fritillary	Medium risk	High risk	High risk
Argynnis aglaja	Dark Green Fritillary	Medium risk	High risk	High risk
Argynnis elisa	Corsican Fritillary	High risk	High risk	High risk
Argynnis laodice	Pallas' fritillary	High risk	High risk	High risk
Argynnis niobe	Niobe Fritillary	High risk	High risk	High risk
Argynnis pandora	Cardinal	High opportunity	High opportunity	High opportunity
Argynnis paphia	Silver-washed Fritillary	Medium risk	Risks and opportunity	Medium opportunity
Aricia agestis	Brown Argus	High opportunity	High opportunity	High opportunity
Aricia anteros	Blue Argus	High risk	High risk	High risk
Aricia artaxerxes	Mountain Argus	High risk	High risk	High risk
Aricia cramera	Southern Brown Argus	High opportunity	High opportunity	High opportunity
Aricia eumedon	Geranium Argus	High risk	High risk	High risk
Aricia montensis	Southern Mountain Argus	High risk	High risk	High risk
Aricia morronensis	Spanish Argus	High risk	High risk	High risk
Aricia nicias	Silvery Argus	High risk	High risk	High risk
Boloria aquilonaris	Cranberry Fritillary	High risk	High risk	High risk
Boloria chariclea	Arctic Fritillary	High risk	High risk	High risk
Boloria dia	Weaver's Fritillary	Limited impact	Medium risk	High risk
Boloria eunomia	Bog Fritillary	High risk	High risk	High risk
Boloria euphrosyne	Pearl-bordered Fritillary	Medium risk	High risk	High risk
Boloria freija	Frejya's Fritillary	High risk	High risk	High risk
Boloria frigga	Frigga's Fritillary	High risk	High risk	High risk
Boloria graeca	Balkan Fritillary	High risk	High risk	High risk
Boloria napaea	Mountain Fritillary	High risk	High risk	High risk
Boloria pales	Shepherd's Fritillary	High risk	High risk	High risk
Boloria polaris	Polar Fritillary	Risks and opportunity	Risks and opportunity	Risks and opportunity
Boloria selene	Small Pearl-bordered Fritillary	Medium risk	Medium risk	High risk
Boloria thore	Thor's Fritillary	High risk	High risk	High risk
Boloria titania	Titania's Fritillary	High risk	High risk	High risk
Brenthis daphne	Marbled Fritillary	High risk	High risk	High risk
Brenthis hecate	Twin-spot Fritillary	High risk	High risk	High risk
Brenthis ino	Lesser Marbled Fritillary	High risk	High risk	High risk
Brintesia circe	Great Banded Grayling	Risks and opportunity	Medium risk	High risk
Cacyreus marshalli	Geranium Bronze	Limited impact	High risk	High risk
Callophrys avis	Chapman's Green Hairstreak	High risk	High risk	High risk
Callophrys rubi	Green Hairstreak	Limited impact	Limited impact	Medium opportunity
Carcharodus alceae	Mallow Skipper	High opportunity	High opportunity	High opportunity
Carcharodus baeticus	Southern Marbled Skipper	High opportunity	High opportunity	Medium opportunity
Carcharodus flocciferus	Tufted Marbled Skipper	High risk	High risk	High risk
Carcharodus lavatherae	Marbled Skipper	Risks and opportunity	Medium risk	High risk

Appendix

Carcharodus orientalis	Oriental Marbled Skipper	High opportunity	High opportunity	High opportunity
Carterocephalus palaemon	Chequered Skipper	High risk	High risk	High risk
Carterocephalus silvicolus	Northern Chequered Skipper	High opportunity	High opportunity	Risks and opportunity
Celastrina argiolus	Holly Blue	High opportunity	High opportunity	High opportunity
Charaxes jasius	Two-tailed Pasha	Medium risk	Risks and opportunity	Risks and opportunity
Chazara briseis	The Hermit	High risk	High risk	High risk
Chazara prieuri	Southern Hermit	High risk	High risk	High risk
Chilades trochylus	Grass jewel	High risk	High risk	High risk
Coenonympha arcania	Pearly Heath	Medium risk	Risks and opportunity	High risk
Coenonympha corinna	Corsican Heath	High risk	High risk	High risk
Coenonympha dorus	Dusky Heath	Risks and opportunity	High risk	High risk
Coenonympha gardetta	Alpine Heath	High risk	High risk	High risk
Coenonympha glycerion	Chestnut Heath	Medium risk	High risk	High risk
Coenonympha hero	Scarce Heath	High risk	High risk	High risk
Coenonympha leander	Russian Heath	High risk	High risk	High risk
Coenonympha oedippus	False Ringlet	High opportunity	High risk	High risk
Coenonympha orientalis	Balkan Heath	High risk	High risk	High risk
Coenonympha pamphilus	Small Heath	Medium risk	Medium risk	Medium risk
Coenonympha rhodopensis	Eastern Large Heath	High risk	High risk	High risk
Coenonympha tullia	Large Heath	High risk	High risk	High risk
Colias alfacariensis	Berger's Clouded Yellow	High opportunity	Medium opportunity	High risk
Colias aurorina	Greek Clouded Yellow	High risk	High risk	High risk
Colias balcanica	Balkan Clouded Yellow	High risk	High risk	High risk
Colias chrysotheme	Lesser Clouded Yellow	High risk	High risk	High risk
Colias crocea	Clouded Yellow	High opportunity	High opportunity	High opportunity
Colias erate	Eastern Pale Clouded Yellow	High opportunity	High opportunity	Medium opportunity
Colias hecla	Northern Clouded Yellow	Risks and opportunity	Risks and opportunity	Risks and opportunity
Colias hyale	Pale Clouded Yellow	Medium risk	Medium risk	High risk
Colias myrmidone	Danube Clouded Yellow	High risk	High risk	High risk
Colias palaeno	Moorland Clouded Yellow	High risk	High risk	High risk
Colias phicomone	Mountain Clouded Yellow	High risk	High risk	High risk
Colias tyche	Pale Arctic clouded yellow	High risk	Risks and opportunity	Risks and opportunity
Colotis evagore	Desert Orange Tip	High opportunity	High opportunity	High opportunity
Cupido alcetas	Provençal short-tailed blue	Medium risk	High risk	High risk
Cupido argiades	Short-tailed blue	Limited impact	Risks and opportunity	High risk
Cupido decoloratus	Eastern Short-tailed Blue	High risk	High risk	High risk
Cupido lorquinii	Lorquin's Blue	High risk	High risk	High risk
Cupido minimus	Little Blue	Medium risk	Medium risk	High risk
Cupido osiris	Osiris Blue	High risk	High risk	High risk
Danaus chrysippus	Plain Tiger	High opportunity	Medium opportunity	Risks and opportunity
Danaus plexippus	Monarch	High risk	High risk	High risk
Erebia aethiopella	False Mnestra Ringlet	High risk	High risk	High risk
Erebia aethiops	Scotch Argus	High risk	High risk	High risk
Erebia alberganus	Almond-eyed Ringlet	High opportunity	High risk	High risk
Erebia calcaria	Lorkovic's Brassy Ringlet	Risks and opportunity	Risks and opportunity	High risk
Erebia cassioides	Common Brassy Ringlet	High risk	High risk	High risk
Erebia christi	Rätzer's Ringlet	High risk	High risk	Risks and opportunity
Erebia claudina	White Speck Ringlet	High risk	High risk	High risk
Erebia disa	Arctic Ringlet	Medium risk	Risks and opportunity	Risks and opportunity
Erebia embla	Lapland Ringlet	High risk	High risk	High risk
Erebia epiphron	Mountain Ringlet	High risk	High risk	High risk
Erebia epistygne	Spring Ringlet	High risk	High risk	High risk
Erebia eriphyle	Eriphyle Ringlet	High risk	High risk	High risk
Erebia euryale	Large Ringlet	High risk	High risk	High risk
Erebia gorge	Silky Ringlet	High risk	High risk	High risk
Erebia gorgone	Gavarnie Ringlet	High risk	High risk	High risk
Erebia hispania	Spanish Brassy Ringlet	High risk	High risk	High risk

Appendix

Erebia lefebvrei	Lefèbvre's Ringlet	High risk	High risk	High risk
Erebia ligea	Arran Brown	High risk	High risk	High risk
Erebia manto	Yellow-spotted Ringlet	High risk	High risk	High risk
Erebia medusa	Woodland Ringlet	Medium risk	High risk	High risk
Erebia melampus	Lesser Mountain Ringlet	High risk	High risk	Risks and opportunity
Erebia melas	Black Ringlet	High risk	High risk	High risk
Erebia meolans	Piedmont Ringlet	High risk	High risk	High risk
Erebia mnestra	Mnestra's Ringlet	High opportunity	Limited impact	High risk
Erebia montana	Marbled Ringlet	High risk	High risk	High risk
Erebia neoridas	Autumn Ringlet	High risk	High risk	High risk
Erebia nivalis	De Lesse's Brassy Ringlet	High risk	High risk	Risks and opportunity
Erebia oeme	Bright-eyed Ringlet	High risk	High risk	High risk
Erebia orientalis	Bulgarian Ringlet	High opportunity	Medium risk	Medium risk
Erebia ottomana	Ottoman Brassy Ringlet	High risk	High risk	High risk
Erebia palarica	Chapman's Ringlet	High risk	High risk	High risk
Erebia pandrose	Dewy Ringlet	High risk	High risk	High risk
Erebia pharte	Blind Ringlet	High risk	High risk	High risk
Erebia pluto	Sooty Ringlet	High risk	High risk	High risk
Erebia polaris	Arctic Woodland Ringlet	Medium risk	Medium risk	Medium risk
Erebia pronoe	Water Ringlet	High risk	High risk	High risk
Erebia rhodopensis	Nicholl's Ringlet	High risk	High risk	High risk
Erebia scipio	Larche Ringlet	High opportunity	High opportunity	High risk
Erebia sthennyo	False Dewy Ringlet	High risk	High risk	High risk
Erebia stiria	Styrian Ringlet	Medium opportunity	Risks and opportunity	Risks and opportunity
Erebia styx	Stygian Ringlet	High opportunity	Limited impact	High risk
Erebia sudetica	Sudeten Ringlet	High risk	High risk	High risk
Erebia triaria	de Prunner's Ringlet	High risk	High risk	High risk
Erebia tyndarus	Swiss Brassy Ringlet	High risk	High risk	High risk
Erebia zapateri	Zapater's Ringlet	High risk	High risk	High risk
Erynnis marloyi	Inky Skipper	High opportunity	High opportunity	Medium opportunity
Erynnis tages	Dingy Skipper	Medium opportunity	Medium opportunity	Medium risk
Euchloe ausonia	Eastern Dappled White	High opportunity	High opportunity	High opportunity
Euchloe bazae	Spanish Greenish Black-tip	High risk	High risk	High risk
Euchloe belemia	Green-striped White	High opportunity	High opportunity	High opportunity
Euchloe crameri	Western Dappled White	High opportunity	High opportunity	Medium risk
Euchloe insularis	Corsican Dappled White	High risk	High risk	High risk
Euchloe penia	Eastern Greenish Black-tip	High risk	High risk	High risk
Euchloe simplonia	Mountain Dappled White	Medium opportunity	Medium opportunity	Medium opportunity
Euchloe tagis	Portuguese Dappled White	High opportunity	High opportunity	High opportunity
Euphydryas aurinia	Marsh Fritillary	High risk	High risk	High risk
Euphydryas cynthia	Cynthia's Fritillary	High risk	High risk	High risk
Euphydryas desfontainii	Spanish Fritillary	High risk	High risk	High risk
Euphydryas iduna	Lapland Fritillary	Risks and opportunity	Risks and opportunity	Risks and opportunity
Euphydryas intermedia	Asian Fritillary	High opportunity	High risk	High risk
Euphydryas maturna	Scarce Fritillary	High risk	High risk	High risk
Favonius quercus	Purple Hairstreak	Medium risk	Medium risk	Medium risk
Gegenes nostrodamus	Mediterranean Skipper	High opportunity	High opportunity	High opportunity
Gegenes pumilio	Pigmy Skipper	Medium opportunity	High opportunity	High opportunity
Glaucopsyche alexis	Green-underside Blue	High opportunity	High opportunity	High opportunity
Glaucopsyche melanops	Black-eyed Blue	High opportunity	High opportunity	Medium opportunity
Gonepteryx cleopatra	Cleopatra	High opportunity	High opportunity	High opportunity
Gonepteryx farinosa	Powdered Brimstone	High opportunity	High opportunity	High opportunity
Gonepteryx rhamni	Brimstone	Medium risk	Medium risk	Medium risk
Hamearis lucina	Duke of Burgundy	High risk	High risk	High risk
Hesperia comma	Silver-spotted Skipper	Medium risk	Medium risk	High risk
Heteropterus morpheus	Large Chequered Skipper	Medium risk	High risk	High risk
Hipparchia aristaeus	Southern Grayling	High risk	High risk	High risk

Appendix

Hipparchia blachieri	Sicilian Grayling	High risk	High risk	High risk
Hipparchia fagi	Woodland Grayling	High risk	High risk	High risk
Hipparchia fatua	Freyer's Grayling	High opportunity	High opportunity	High opportunity
Hipparchia fidia	Striped Grayling	High opportunity	Medium opportunity	Risks and opportunity
Hipparchia hermione	Rock Grayling	High risk	High risk	High risk
Hipparchia leighebi	Eolian Grayling	High opportunity	High opportunity	High opportunity
Hipparchia mersina	Samos Grayling	High risk	Medium opportunity	High opportunity
Hipparchia neomiris	Corsican Grayling	High risk	High risk	High risk
Hipparchia pellucida	Cyprus grayling	High opportunity	High opportunity	High opportunity
Hipparchia semele	Grayling	Medium opportunity	Risks and opportunity	Risks and opportunity
Hipparchia senthes	Balkan Grayling	High opportunity	High opportunity	High opportunity
Hipparchia statilinus	Tree Grayling	Medium opportunity	Medium opportunity	Medium opportunity
Hipparchia syriaca	Eastern Rock Grayling	High opportunity	Medium opportunity	High risk
Hipparchia volgensis	Delattin's Grayling	Medium risk	High risk	High risk
Hyponephele lupina	Oriental Meadow Brown	High opportunity	High opportunity	High opportunity
Hyponephele lycaon	Dusky Meadow Brown	Medium risk	High risk	High risk
Iolana iolas	Iolas Blue	Medium risk	High risk	High risk
Iphiclides podalirius	Scarce Swallowtail	High opportunity	High opportunity	High opportunity
Issoria lathonia	Queen of Spain Fritillary	High opportunity	High opportunity	Medium opportunity
Kirinia climene	Lesser Lattice Brown	High risk	High risk	High risk
Kirinia roxelana	Lattice Brown	High opportunity	High opportunity	High opportunity
Laeosopis roboris	Spanish Purple Hairstreak	Medium risk	Medium risk	High opportunity
Lampides boeticus	Long-tailed Blue	High opportunity	High opportunity	High opportunity
Lasiommata maera	Large Wall Brown	Medium risk	Medium risk	High risk
Lasiommata megera	Wall Brown	High opportunity	High opportunity	High opportunity
Lasiommata paramegaera	Corsican Wall Brown	High risk	High risk	High risk
Lasiommata petropolitana	Northern Wall Brown	High risk	High risk	High risk
Leptidea duponcheli	Eastern Wood White	High opportunity	High opportunity	High opportunity
Leptidea morsei	Fenton's Wood White	High risk	High risk	High risk
Leptidea sinapis	Wood White	Limited impact	Risks and opportunity	Medium risk
Leptotes pirithous	Lang's Short-tailed Blue	High opportunity	High opportunity	High opportunity
Libythea celtis	Nettle-tree Butterfly	Medium risk	High risk	High risk
Limenitis camilla	White Admiral	High risk	High risk	High risk
Limenitis populi	Poplar Admiral	High risk	High risk	High risk
Limenitis reducta	Southern White Admiral	Medium risk	High risk	High risk
Lopinga achine	Woodland Brown	Medium risk	Medium risk	High risk
Lycaena alciphron	Purple-shot Copper	High risk	High risk	High risk
Lycaena dispar	Large Copper	High opportunity	High opportunity	High opportunity
Lycaena helle	Violet Copper	High risk	High risk	High risk
Lycaena hippothoe	Purple-edged Copper	Medium risk	High risk	Risks and opportunity
Lycaena ottomana	Grecian Copper	High opportunity	Medium risk	High risk
Lycaena phlaeas	Small Copper	High opportunity	High opportunity	High opportunity
Lycaena thersamon	Lesser Fiery Copper	High opportunity	High opportunity	High opportunity
Lycaena thetis	Fiery Copper	High opportunity	High opportunity	Risks and opportunity
Lycaena tityrus	Sooty Copper	High risk	High risk	High risk
Lycaena virgaureae	Scarce Copper	Medium risk	High risk	High risk
Maniola halicarnassus	Thomson's Meadow Brown	High opportunity	High opportunity	High opportunity
Maniola jurtina	Meadow Brown	Risks and opportunity	High opportunity	Medium opportunity
Maniola nurag	Sardinian Meadow Brown	High risk	High risk	High risk
Maniola telmessia	Telmessia Meadow Brown	High opportunity	High opportunity	High opportunity
Melanargia arge	Italian Marbled White	High risk	High risk	High risk
Melanargia galathea	Marbled White	Medium risk	Medium risk	High risk
Melanargia ines	Spanish Marbled White	High opportunity	Medium opportunity	Risks and opportunity
Melanargia lachesis	Iberian Marbled White	High risk	High risk	High risk
Melanargia larissa	Balkan Marbled White	Medium opportunity	Medium risk	High risk
Melanargia occitanica	Western Marbled White	High opportunity	High opportunity	Risks and opportunity
Melanargia pherusa	Sicilian Marbled White	High risk	High risk	High risk

Appendix

Melanargia russiae	Esper's Marbled White	High risk	High risk	High risk
Melitaea aetherie	Aetherie Fritillary	High risk	High risk	High risk
Melitaea arduinna	Freyer's Fritillary	High risk	High risk	High risk
Melitaea asteria	Little Fritillary	High risk	Medium risk	Medium risk
Melitaea athalia	Heath Fritillary	Medium risk	Medium risk	High risk
Melitaea aurelia	Nickerl's fritillary	Medium risk	High risk	High risk
Melitaea britomartis	Assmann's Fritillary	Medium opportunity	Medium risk	High risk
Melitaea cinxia	Glanville Fritillary	Medium opportunity	Medium opportunity	Risks and opportunity
Melitaea deione	Provençal fritillary	High risk	High risk	High risk
Melitaea diamina	False Heath Fritillary	Medium risk	High risk	High risk
Melitaea didyma	Spotted Fritillary	High opportunity	High opportunity	Medium risk
Melitaea parthenoides	Meadow fritillary	High risk	High risk	High risk
Melitaea phoebe	Knapweed Fritillary	Medium opportunity	Risks and opportunity	High risk
Melitaea trivia	Lesser Spotted Fritillary	Medium opportunity	Risks and opportunity	High risk
Melitaea varia	Grisons Fritillary	High risk	High risk	High risk
Minois dryas	Dryad	Medium risk	High risk	High risk
Neptis rivularis	Hungarian Glider	High risk	High risk	High risk
Neptis sappho	Common Glider	High risk	High risk	High risk
Nymphalis antiopa	Camberwell Beauty	Medium risk	High risk	High risk
Nymphalis c-album	Comma	Medium risk	Medium opportunity	Medium opportunity
Nymphalis egea	Southern Comma	High opportunity	High opportunity	Medium opportunity
Nymphalis l-album	False Comma	High risk	High risk	High risk
Nymphalis polychloros	Large Tortoiseshell	High opportunity	High opportunity	High opportunity
Nymphalis xanthomelas	Yellow-legged Tortoiseshell	Medium risk	High risk	High risk
Ochlodes sylvanus	Large Skipper	Medium risk	Medium risk	High risk
Oeneis bore	Arctic Grayling	Risks and opportunity	Risks and opportunity	Risks and opportunity
Oeneis glacialis	Alpine Grayling	High risk	High risk	High risk
Oeneis jutta	Baltic Grayling	High risk	High risk	High risk
Oeneis norna	Norse Grayling	High risk	High risk	High risk
Papilio alexanor	Southern Swallowtail	Medium risk	High risk	High risk
Papilio hospiton	Corsican Swallowtail	High risk	High risk	High risk
Papilio machaon	Swallowtail	High opportunity	High opportunity	High opportunity
Pararge aegeria	Speckled Wood	Medium opportunity	Medium opportunity	Medium opportunity
Parnassius apollo	Apollo	High risk	High risk	High risk
Parnassius mnemosyne	Clouded Apollo	High risk	High risk	High risk
Parnassius phoebus	Small Apollo	High risk	High risk	High risk
Pelopidas thrax	Millet Skipper	High risk	High risk	High risk
Phengaris alcon	Alcon Blue	High risk	High risk	High risk
Phengaris arion	Large Blue	High risk	High risk	High risk
Phengaris nausithous	Dusky Large Blue	High risk	High risk	High risk
Phengaris teleius	Scarce Large Blue	High risk	High risk	High risk
Pieris brassicae	Large White	Medium opportunity	High opportunity	High opportunity
Pieris bryoniae	Mountain Green-veined White	High risk	High risk	High risk
Pieris ergane	Mountain Small White	High risk	High risk	High risk
Pieris krueperi	Krueper's Small White	High risk	High risk	High risk
Pieris mannii	Southern Small White	High risk	High risk	High risk
Pieris napi	Green-veined White	Limited impact	Medium risk	Medium risk
Pieris rapae	Small White	Medium opportunity	High opportunity	High opportunity
Plebejus aquilo	Arctic Blue	Risks and opportunity	Risks and opportunity	Risks and opportunity
Plebejus argus	Silver-studded Blue	Medium risk	Medium risk	High risk
Plebejus argyrognomon	Reverdin's Blue	Medium risk	Medium risk	High risk
Plebejus bellieri	Bellier's Blue	High risk	High risk	High risk
Plebejus dardanus	Balkan Blue	Risks and opportunity	Risks and opportunity	Risks and opportunity
Plebejus glandon	Glandon Blue	High risk	High risk	High risk
Plebejus hespericus	Spanish Zephyr Blue	High risk	High risk	High risk
Plebejus idas	Idas Blue	Medium risk	Medium risk	High risk
Plebejus loewii	Loew's Blue	High opportunity	High opportunity	High opportunity

Appendix

Plebejus optilete	Cranberry Blue	High risk	High risk	High risk
Plebejus orbitulus	Alpine Argus	High risk	Medium risk	Risks and opportunity
Plebejus psyloritus	Cretan Argus	High opportunity	High opportunity	High opportunity
Plebejus pylaon	Zephyr Blue	Medium risk	High risk	High risk
Plebejus pyrenaicus	Gavarnie Blue	High risk	High risk	High risk
Plebejus trappi	Alpine Zephyr Blue	Risks and opportunity	Risks and opportunity	Risks and opportunity
Plebejus zullichi	Zullich's Blue	High risk	Medium risk	Medium risk
Polyommatus admetus	Anomalous Blue	High risk	High risk	High risk
Polyommatus amandus	Amanda's Blue	Medium risk	Medium risk	Medium risk
Polyommatus aroaniensis	Grecian Anomalous Blue	Risks and opportunity	Medium risk	High risk
Polyommatus bellargus	Adonis Blue	High opportunity	Medium opportunity	High risk
Polyommatus coridon	Chalk-hill Blue	Medium risk	High risk	High risk
Polyommatus damon	Damon Blue	High risk	High risk	High risk
Polyommatus daphnis	Meleager's Blue	Medium opportunity	Medium risk	High risk
Polyommatus dolus	Furry Blue	High risk	High risk	High risk
Polyommatus dorylas	Turquoise Blue	High risk	High risk	High risk
Polyommatus eros	Eros Blue	High risk	High risk	High risk
Polyommatus escheri	Escher's Blue	High risk	High risk	High risk
Polyommatus fabressei	Oberthür's Anomalous Blue	High risk	High risk	High risk
Polyommatus fulgens	Catalonian Furry Blue	High risk	High risk	High risk
Polyommatus hispanus	Provence Chalkhill Blue	High risk	High risk	High risk
Polyommatus humedasae	Piedmont Anomalous Blue	High risk	High risk	High risk
Polyommatus icarus	Common Blue	High opportunity	High opportunity	High opportunity
Polyommatus nivescens	Mother-of-pearl Blue	High risk	High risk	High risk
Polyommatus ripartii	Ripart's Anomalous Blue	High risk	High risk	High risk
Polyommatus semiargus	Mazarine Blue	Medium risk	High risk	High risk
Polyommatus thersites	Chapman's Blue	High opportunity	High opportunity	High risk
Pontia callidice	Peak White	High risk	High risk	High risk
Pontia chloridice	Small Bath White	High risk	High risk	High risk
Pontia daplidice	Bath White	High opportunity	High opportunity	High opportunity
Pseudochazara anthelea	White-banded Grayling	Medium risk	High risk	High risk
Pseudochazara cingovskii	Macedonian Grayling	High risk	High risk	High risk
Pseudochazara geyeri	Grey Asian Grayling	High risk	High risk	High risk
Pseudochazara graeca	Grecian Grayling	Medium risk	High risk	High risk
Pseudochazara mniszechii	Dark Grayling	High risk	High risk	High risk
Pseudochazara orestes	Dils' Grayling	Medium risk	High risk	High risk
Pseudochazara williamsi	Nevada Grayling	High risk	High risk	High risk
Pyrgus alveus	Large Grizzled Skipper	Medium risk	High risk	High risk
Pyrgus andromedae	Alpine Grizzled Skipper	High risk	High risk	High risk
Pyrgus armoricanus	Oberthür's Grizzled Skipper	High risk	High risk	High risk
Pyrgus bellieri	Foulquier’s Grizzled Skipper	High risk	High risk	High risk
Pyrgus cacaliae	Dusky Grizzled Skipper	Medium opportunity	High risk	High risk
Pyrgus carlinae	Carline Skipper	High opportunity	High risk	High risk
Pyrgus carthami	Safflower Skipper	Medium risk	High risk	High risk
Pyrgus centaureae	Northern Grizzled Skipper	High risk	High risk	High risk
Pyrgus cinarae	Sandy Grizzled Skipper	High risk	High risk	High risk
Pyrgus cirsii	Cinquefoil Skipper	High risk	High risk	High risk
Pyrgus malvae	Grizzled Skipper	Medium risk	Medium risk	Medium risk
Pyrgus melotis	Aegean Skipper	High risk	Risks and opportunity	Medium opportunity
Pyrgus onopordi	Rosy Grizzled Skipper	High risk	High risk	High risk
Pyrgus serratulae	Olive Skipper	High risk	High risk	High risk
Pyrgus sidae	Yellow-banded Skipper	Medium risk	High risk	High risk
Pyrgus warrenensis	Warren's Skipper	High risk	High risk	High risk
Pyronia bathseba	Spanish Gatekeeper	High opportunity	High opportunity	Medium opportunity
Pyronia cecilia	Southern Gatekeeper	High opportunity	Medium opportunity	Risks and opportunity
Pyronia tithonus	Gatekeeper	Medium risk	High risk	High risk
Satyrium acaciae	Sloe Hairstreak	High risk	High risk	High risk

Appendix

Satyrium esculi	False Ilex Hairstreak	High opportunity	High opportunity	Medium opportunity
Satyrium ilicis	Ilex Hairstreak	High risk	High risk	High risk
Satyrium ledereri	Orange-banded Hairstreak	High risk	High risk	High risk
Satyrium pruni	Black Hairstreak	High risk	High risk	High risk
Satyrium spini	Blue-spot Hairstreak	High opportunity	High opportunity	Risks and opportunity
Satyrium w-album	White-letter Hairstreak	Medium risk	Medium risk	High risk
Satyrus actaea	Black Satyr	Risks and opportunity	High risk	High risk
Satyrus ferula	Great Sooty Satyr	Medium risk	High risk	High risk
Scolitantides abencerragus	False Baton Blue	High risk	High risk	High risk
Scolitantides barbagiae	Sardinian Blue	High risk	High risk	High risk
Scolitantides baton	Baton Blue	High risk	High risk	High risk
Scolitantides bavius	Bavius Blue	High risk	High risk	High risk
Scolitantides orion	Chequered Blue	Medium opportunity	Risks and opportunity	High risk
Scolitantides panoptes	Panoptes Blue	Risks and opportunity	Medium risk	High risk
Scolitantides vicrama	Eastern Baton Blue	High opportunity	High opportunity	High opportunity
Spialia orbifer	Orbed Red-underwing Skipper	High opportunity	High opportunity	High opportunity
Spialia phlomidis	Persian Skipper	High risk	High risk	High risk
Spialia sertorius	Red Underwing Skipper	High opportunity	Risks and opportunity	High risk
Spialia therapne	Corsican Red-underwing Skipper	High risk	High risk	High risk
Syrichtus cribrellum	Spinose Skipper	Risks and opportunity	High risk	High risk
Syrichtus proto	Sage Skipper	High opportunity	High opportunity	High opportunity
Syrichtus tessellum	Tessellated Skipper	High opportunity	High opportunity	High opportunity
Tarucus balkanicus	Little Tiger Blue	High opportunity	High opportunity	Risks and opportunity
Tarucus theophrastus	Common Tiger Blue	Risks and opportunity	Risks and opportunity	Risks and opportunity
Thecla betulae	Brown Hairstreak	Medium risk	High risk	High risk
Thymelicus acteon	Lulworth Skipper	High opportunity	Medium opportunity	Risks and opportunity
Thymelicus hyrax	Levantine Skipper	High opportunity	High opportunity	High opportunity
Thymelicus lineola	Essex Skipper	Medium risk	Medium risk	High risk
Thymelicus sylvestris	Small Skipper	Medium risk	High risk	High risk
Tomares ballus	Provence Hairstreak	High opportunity	High opportunity	Medium opportunity
Tomares nogelii	Nogel's Hairstreak	Risks and opportunity	Risks and opportunity	Risks and opportunity
Vanessa atalanta	Red Admiral	High opportunity	High opportunity	High opportunity
Vanessa virginiensis	American Painted Lady	High risk	High risk	High risk
Ypthima asterope	African Ringlet	High opportunity	High opportunity	High opportunity
Zegris eupheme	Sooty Orange Tip	Risks and opportunity	Medium risk	High risk
Zerynthia cassandra	Italian Festoon	High risk	High risk	High risk
Zerynthia cerisyi	Eastern Festoon	High opportunity	High opportunity	High opportunity
Zerynthia cretica	Cretan Festoon	High opportunity	High opportunity	High opportunity
Zerynthia polyxena	Southern Festoon	High opportunity	High opportunity	High opportunity
Zerynthia rumina	Spanish Festoon	High opportunity	High opportunity	Medium risk
Zizeeria knysna	African Grass Blue	Medium opportunity	Risks and opportunity	Risks and opportunity

Table S3.2. Probability of risk category assignment for the species not assessed using the full climate vulnerability framework. Probabilities are based on the high climate scenario.

	Risk category probability					
Birds	**High opportunity**	**Medium opportunity**	**Limited impact**	**Risks and opportunity**	**Medium risk**	**High risk**
Acridotheres cristatellus	0.071	0.035	0.001	0.106	0.119	0.668
Acridotheres tristis	0.460	0.168	0.000	0.023	0.023	0.324
Aix galericulata	0.162	0.071	0.001	0.078	0.084	0.604
Aix sponsa	0.156	0.070	0.001	0.076	0.082	0.617
Alopochena egyptiacus	0.175	0.076	0.001	0.073	0.078	0.597
Amandava amandava	0.462	0.167	0.000	0.024	0.024	0.323
Anser albifrons	0.010	0.006	0.001	0.169	0.206	0.607
Anthropoides virgo	0.180	0.078	0.001	0.073	0.077	0.591
Anthus berthelotii	0.583	0.195	0.000	0.012	0.011	0.200
Anthus hodgsoni	0.089	0.044	0.001	0.100	0.120	0.646
Apus unicolor	0.582	0.195	0.000	0.012	0.011	0.200
Aquila nipalensis	0.116	0.054	0.001	0.089	0.098	0.643
Bucanetes mongolicus	0.233	0.098	0.000	0.057	0.061	0.550
Bulweria bulwerii	0.571	0.192	0.000	0.013	0.012	0.212
Calidris alba	0.015	0.009	0.001	0.157	0.191	0.627
Calidris canutus	0.013	0.008	0.001	0.164	0.197	0.619
Callipepla californica	0.219	0.093	0.001	0.060	0.064	0.563
Carpodacus rubicilla	0.186	0.081	0.001	0.067	0.072	0.592
Charadrius asiaticus	0.055	0.028	0.001	0.115	0.135	0.667
Charadrius leschenaultii	0.150	0.067	0.001	0.077	0.083	0.622
Chettusia gregaria	0.060	0.031	0.001	0.112	0.131	0.666
Chettusia leucura	0.046	0.024	0.001	0.121	0.139	0.669
Chrysolophus amherstiae	0.158	0.070	0.001	0.075	0.081	0.616
Chrysolophus pictus	0.165	0.073	0.001	0.074	0.080	0.608
Colinus virginia	0.272	0.110	0.000	0.052	0.054	0.512
Columba trocaz	0.581	0.195	0.000	0.012	0.011	0.201
Cygnus columbia	0.031	0.018	0.001	0.129	0.164	0.657
Emberiza bruniceps	0.046	0.024	0.001	0.121	0.139	0.669
Emberiza leucceophalos	0.081	0.040	0.001	0.101	0.113	0.664
Estrilda astrild	0.557	0.180	0.000	0.017	0.015	0.231
Ficedula semitorquata	0.350	0.129	0.000	0.046	0.042	0.432
Francolinus francolinus	0.172	0.076	0.001	0.072	0.078	0.602
Gallinago stenura	0.086	0.042	0.001	0.101	0.117	0.653
Gavia adamsii	0.005	0.003	0.001	0.191	0.239	0.561
Hieraaetus fasciatu	0.597	0.147	0.000	0.033	0.018	0.205
Hippolais caligata	0.078	0.038	0.001	0.103	0.116	0.664
Larus armenicus	0.113	0.053	0.001	0.088	0.097	0.648
Larus glaucoids	0.021	0.012	0.001	0.146	0.175	0.645
Larus ichthyaetus	0.156	0.070	0.001	0.077	0.083	0.613
Larus sabini	0.013	0.008	0.001	0.164	0.197	0.619
Locustella lanceolata	0.083	0.041	0.001	0.101	0.115	0.660
Luscinia calliope	0.083	0.041	0.001	0.101	0.115	0.659
Melanocorypha leucoptera	0.109	0.051	0.001	0.090	0.099	0.651
Meleagris gallopavo	0.146	0.066	0.001	0.078	0.085	0.625
Merops superciliosus	0.105	0.050	0.001	0.091	0.101	0.653
Oenanthe deserti	0.046	0.024	0.001	0.121	0.139	0.669
Oenanthe finschii	0.234	0.098	0.000	0.057	0.061	0.550
Oenanthe xanthoprymna	0.233	0.098	0.000	0.057	0.061	0.550

Oxyura jamaicensis	0.147	0.066	0.001	0.083	0.090	0.614
Pagophilae burnea	0.011	0.007	0.001	0.161	0.205	0.614
Parus cyanus	0.080	0.039	0.001	0.102	0.115	0.663
Phaethon aethereus	0.512	0.181	0.000	0.018	0.018	0.272
Phoenicopterus ruber	0.567	0.190	0.000	0.013	0.013	0.217
Phylloscopus inornatus	0.087	0.043	0.001	0.101	0.118	0.650
Phylloscopus lorenzii	0.450	0.165	0.000	0.025	0.025	0.336
Pluvialis squatarola	0.023	0.014	0.001	0.137	0.178	0.647
Polysticta stelleri	0.005	0.003	0.001	0.192	0.239	0.561
Prunella atrogularis	0.082	0.040	0.001	0.101	0.114	0.662
Prunella montanella	0.085	0.042	0.001	0.101	0.117	0.655
Psittacula krameri	0.261	0.105	0.001	0.057	0.057	0.519
Pterodro feae	0.548	0.189	0.000	0.014	0.014	0.234
Pterodro madeira	0.581	0.195	0.000	0.012	0.011	0.201
Puffinus assimilis	0.567	0.190	0.000	0.013	0.013	0.217
Pyrrhula murina	0.576	0.195	0.000	0.012	0.012	0.206
Serinus canaria	0.568	0.189	0.000	0.014	0.013	0.216
Serinus pusillus	0.346	0.135	0.000	0.039	0.040	0.441
Stercorarius pomarinus	0.039	0.022	0.001	0.123	0.154	0.661
Sterna fuscata	0.571	0.193	0.000	0.012	0.012	0.211
Sylvia mystacea	0.060	0.030	0.001	0.112	0.127	0.670
Syrmaticus reevesi	0.237	0.098	0.001	0.061	0.062	0.541
Tetraogallus caspius	0.112	0.052	0.001	0.090	0.099	0.647
Tetraogallus caucasicus	0.170	0.074	0.001	0.074	0.080	0.601
Tetrao mlokosiewiczi	0.139	0.063	0.001	0.084	0.092	0.621
Turdus ruficollis	0.086	0.042	0.001	0.101	0.118	0.652
Turnix sylvatica	0.632	0.203	0.000	0.008	0.007	0.150
Zoothera dauma	0.085	0.042	0.001	0.101	0.118	0.653

Butterflies	Risk category probability					
	High opportunity	Medium opportunity	Limited impact	Risks and opportunity	Medium risk	High risk
Apharitis cilissa	0.2122	0.0905	0.0005	0.0621	0.0660	0.5687
Apharitis maxima	0.2337	0.0977	0.0005	0.0585	0.0614	0.5481
Archon apollinaris	0.2719	0.1104	0.0005	0.0517	0.0534	0.5122
Aricia crassipunctus	0.0595	0.0304	0.0007	0.1122	0.1299	0.6674
Aricia hyacinthus	0.2104	0.0898	0.0005	0.0626	0.0665	0.5702
Aricia isauricus	0.1311	0.0600	0.0006	0.0839	0.0919	0.6325
Aricia teberdina	0.0197	0.0113	0.0007	0.1495	0.1766	0.6421
Aricia torulensis	0.1495	0.0673	0.0006	0.0768	0.0834	0.6224
Boloria caucasica	0.0554	0.0284	0.0007	0.1148	0.1313	0.6694
Boloria improba	0.0015	0.0011	0.0007	0.2238	0.2956	0.4774
Borbo borbonica	0.5928	0.1976	0.0001	0.0105	0.0103	0.1887
Brenthis mofidii	0.1255	0.0579	0.0006	0.0844	0.0925	0.6392
Callophrys danchenkoi	0.0831	0.0405	0.0007	0.1005	0.1128	0.6626
Callophrys mystaphia	0.0792	0.0387	0.0007	0.1019	0.1140	0.6654
Callophrys paulae	0.1013	0.0481	0.0007	0.0936	0.1044	0.6520
Carcharodus stauderi	0.3067	0.1208	0.0004	0.0468	0.0473	0.4780
Catopsilia florella	0.0497	0.0257	0.0007	0.1188	0.1353	0.6698
Chazara bischoffi	0.0907	0.0440	0.0007	0.0986	0.1130	0.6530
Chazara egina	0.1347	0.0615	0.0006	0.0817	0.0892	0.6324
Chazara persephone	0.1616	0.0710	0.0007	0.0802	0.0862	0.6003
Chilades galba	0.6231	0.2004	0.0001	0.0086	0.0081	0.1596
Coenonympha saadi	0.3246	0.1249	0.0004	0.0458	0.0449	0.4594
Coenonympha symphyta	0.0240	0.0135	0.0008	0.1420	0.1694	0.6503
Coenonympha thyrsis	0.6139	0.1977	0.0001	0.0095	0.0090	0.1697
Colias caucasica	0.0385	0.0205	0.0007	0.1273	0.1474	0.6656
Colias chlorocoma	0.0741	0.0367	0.0007	0.1046	0.1187	0.6652
Colias thisoa	0.0492	0.0257	0.0007	0.1186	0.1377	0.6681
Colotis fausta	0.3711	0.1416	0.0004	0.0357	0.0359	0.4154
Cupido staudingeri	0.0540	0.0276	0.0007	0.1158	0.1316	0.6702
Eogenes alcides	0.0860	0.0417	0.0007	0.0993	0.1115	0.6608
Eogenes lesliei	0.3502	0.1368	0.0004	0.0372	0.0385	0.4368
Erebia flavofasciata	0.0198	0.0114	0.0008	0.1483	0.1776	0.6421
Erebia graucasica	0.0379	0.0203	0.0007	0.1276	0.1484	0.6650
Erebia hewitsonii	0.0420	0.0222	0.0007	0.1242	0.1438	0.6671
Erebia melancholica	0.0459	0.0240	0.0007	0.1212	0.1399	0.6682
Euapatura mirza	0.2246	0.0949	0.0005	0.0595	0.0630	0.5575
Euphydryas orientalis	0.1716	0.0758	0.0006	0.0710	0.0765	0.6046
Glaucopsyche astraea	0.1632	0.0723	0.0006	0.0748	0.0806	0.6085
Hipparchia christenseni	0.6273	0.2028	0.0001	0.0079	0.0077	0.1542
Hipparchia cretica	0.6132	0.1980	0.0001	0.0095	0.0090	0.1702
Hipparchia parisatis	0.1447	0.0652	0.0006	0.0800	0.0869	0.6226
Hypolimnas misippus	0.6149	0.2011	0.0001	0.0088	0.0086	0.1664
Hyponephele cadusia	0.0802	0.0392	0.0007	0.1015	0.1134	0.6651
Hyponephele kocaki	0.1180	0.0549	0.0006	0.0867	0.0952	0.6445
Hyponephele naricoides	0.0797	0.0391	0.0007	0.1020	0.1151	0.6634
Hyponephele urartua	0.0732	0.0362	0.0007	0.1050	0.1183	0.6666
Hyponephele wagneri	0.3367	0.1289	0.0004	0.0433	0.0426	0.4481
Lasiommata menava	0.1879	0.0818	0.0005	0.0672	0.0720	0.5905
Lycaena asabinus	0.1380	0.0625	0.0007	0.0840	0.0919	0.6230
Lycaena candens	0.0704	0.0353	0.0007	0.1066	0.1235	0.6635
Lycaena euphratica	0.1449	0.0655	0.0006	0.0789	0.0858	0.6242

Lycaena lampon	0.0843	0.0409	0.0007	0.0997	0.1113	0.6631
Lycaena ochimus	0.1624	0.0715	0.0007	0.0785	0.0843	0.6027
Lycaena phoenicurus	0.0412	0.0218	0.0007	0.1252	0.1440	0.6672
Maniola chia	0.5367	0.1864	0.0002	0.0154	0.0153	0.2461
Maniola megala	0.5435	0.1855	0.0002	0.0155	0.0149	0.2403
Melanargia wiskotti	0.5657	0.1907	0.0002	0.0132	0.0128	0.2173
Melitaea caucasogenita	0.0200	0.0114	0.0007	0.1489	0.1763	0.6426
Melitaea collina	0.3814	0.1431	0.0004	0.0355	0.0349	0.4048
Melitaea interrupta	0.0491	0.0256	0.0007	0.1187	0.1376	0.6682
Melitaea persea	0.2181	0.0915	0.0006	0.0639	0.0666	0.5593
Muschampia plurimacula	0.1101	0.0517	0.0006	0.0894	0.0986	0.6495
Muschampia poggei	0.2396	0.0991	0.0005	0.0587	0.0609	0.5412
Muschampia proteides	0.1814	0.0790	0.0006	0.0704	0.0752	0.5934
Nymphalis l album	0.0749	0.0373	0.0007	0.1046	0.1211	0.6614
Papilio demoleus	0.5769	0.1948	0.0002	0.0118	0.0116	0.2047
Parnassius nordmanni	0.0166	0.0097	0.0007	0.1547	0.1844	0.6338
Pieris bowdeni	0.0466	0.0244	0.0007	0.1205	0.1399	0.6679
Plebejus alcedo	0.0879	0.0427	0.0007	0.0991	0.1124	0.6573
Plebejus christophi	0.0479	0.0248	0.0007	0.1201	0.1371	0.6695
Plebejus eurypilus	0.2149	0.0881	0.0007	0.0730	0.0739	0.5494
Plebejus morgianus	0.0863	0.0417	0.0007	0.0988	0.1101	0.6624
Plebejus rosei	0.0792	0.0387	0.0007	0.1019	0.1140	0.6654
Polyommatus actis	0.1811	0.0791	0.0006	0.0694	0.0744	0.5955
Polyommatus aedon	0.0565	0.0291	0.0007	0.1138	0.1330	0.6669
Polyommatus alcestis	0.1323	0.0604	0.0007	0.0846	0.0928	0.6292
Polyommatus altivagans	0.0565	0.0288	0.0007	0.1142	0.1301	0.6697
Polyommatus anticarmon	0.0949	0.0454	0.0007	0.0953	0.1061	0.6576
Polyommatus antidolus	0.0684	0.0341	0.0007	0.1074	0.1213	0.6681
Polyommatus artvinensis	0.0290	0.0160	0.0007	0.1365	0.1600	0.6577
Polyommatus aserbeidschanus	0.0521	0.0269	0.0007	0.1169	0.1340	0.6694
Polyommatus baytopi	0.0814	0.0397	0.0007	0.1011	0.1135	0.6636
Polyommatus bilgini	0.1060	0.0500	0.0006	0.0908	0.1003	0.6522
Polyommatus buzulmavi	0.1158	0.0540	0.0006	0.0875	0.0963	0.6458
Polyommatus caeruleus	0.0479	0.0248	0.0007	0.1201	0.1371	0.6695
Polyommatus carmon	0.1363	0.0620	0.0007	0.0832	0.0910	0.6269
Polyommatus cilicius	0.2156	0.0918	0.0005	0.0611	0.0649	0.5660
Polyommatus ciloicus	0.0633	0.0318	0.0007	0.1102	0.1243	0.6697
Polyommatus coelestinus	0.1013	0.0483	0.0007	0.0950	0.1076	0.6471
Polyommatus cornelia	0.2616	0.1045	0.0005	0.0585	0.0584	0.5165
Polyommatus corydonius	0.0509	0.0267	0.0008	0.1166	0.1395	0.6655
Polyommatus cyaneus	0.0543	0.0279	0.0007	0.1154	0.1326	0.6691
Polyommatus dama	0.3088	0.1238	0.0004	0.0436	0.0454	0.4781
Polyommatus damocles	0.0997	0.0474	0.0007	0.0933	0.1033	0.6558
Polyommatus dantchenkoi	0.1035	0.0489	0.0006	0.0918	0.1015	0.6537
Polyommatus demavendi	0.1026	0.0486	0.0007	0.0929	0.1033	0.6520
Polyommatus dezinus	0.0633	0.0318	0.0007	0.1102	0.1243	0.6697
Polyommatus diana	0.0484	0.0251	0.0007	0.1195	0.1372	0.6690
Polyommatus eriwanensis	0.0342	0.0185	0.0007	0.1312	0.1527	0.6627
Polyommatus erzindjanensis	0.0732	0.0362	0.0007	0.1049	0.1176	0.6674
Polyommatus fatima	0.0878	0.0424	0.0007	0.0984	0.1100	0.6607
Polyommatus firdussii	0.0942	0.0454	0.0007	0.0970	0.1101	0.6526
Polyommatus golgus	0.3286	0.1298	0.0004	0.0407	0.0421	0.4584
Polyommatus guezelmavi	0.1872	0.0816	0.0005	0.0671	0.0721	0.5915
Polyommatus haigi	0.0840	0.0408	0.0007	0.0998	0.1115	0.6632
Polyommatus hopfferi	0.1212	0.0561	0.0007	0.0877	0.0969	0.6374
Polyommatus huberti	0.0535	0.0276	0.0007	0.1157	0.1343	0.6681

Polyommatus interjectus	0.0753	0.0371	0.0007	0.1038	0.1163	0.6668
Polyommatus iphicarmon	0.1546	0.0693	0.0006	0.0753	0.0817	0.6185
Polyommatus iphigenia	0.1115	0.0523	0.0007	0.0914	0.1023	0.6417
Polyommatus karacetinae	0.0633	0.0318	0.0007	0.1102	0.1243	0.6697
Polyommatus kurdistanicus	0.1035	0.0489	0.0006	0.0918	0.1015	0.6537
Polyommatus lycius	0.2843	0.1157	0.0004	0.0476	0.0499	0.5020
Polyommatus menalcas	0.1774	0.0769	0.0006	0.0742	0.0788	0.5921
Polyommatus merhaba	0.0362	0.0195	0.0007	0.1293	0.1503	0.6641
Polyommatus mithridates	0.1420	0.0642	0.0006	0.0809	0.0881	0.6242
Polyommatus myrrha	0.1546	0.0692	0.0006	0.0763	0.0826	0.6168
Polyommatus ninae	0.0531	0.0276	0.0007	0.1158	0.1356	0.6672
Polyommatus orphicus	0.1813	0.0792	0.0006	0.0693	0.0743	0.5952
Polyommatus ossmar	0.1584	0.0703	0.0006	0.0770	0.0831	0.6105
Polyommatus phyllis	0.0572	0.0294	0.0007	0.1134	0.1319	0.6673
Polyommatus pierceae	0.0787	0.0385	0.0007	0.1023	0.1147	0.6651
Polyommatus poseidon	0.1416	0.0639	0.0007	0.0822	0.0896	0.6220
Polyommatus putnami	0.0363	0.0195	0.0007	0.1294	0.1496	0.6644
Polyommatus schuriani	0.2192	0.0931	0.0005	0.0605	0.0642	0.5626
Polyommatus sertavulensis	0.2898	0.1169	0.0004	0.0476	0.0493	0.4960
Polyommatus sigberti	0.1634	0.0725	0.0006	0.0739	0.0798	0.6098
Polyommatus surakovi	0.1331	0.0609	0.0006	0.0816	0.0892	0.6346
Polyommatus syriacus	0.2464	0.1025	0.0005	0.0553	0.0581	0.5373
Polyommatus tankeri	0.0433	0.0228	0.0007	0.1233	0.1420	0.6678
Polyommatus theresiae	0.0723	0.0357	0.0007	0.1053	0.1182	0.6677
Polyommatus turcicolus	0.0789	0.0387	0.0007	0.1022	0.1147	0.6649
Polyommatus turcicus	0.0681	0.0342	0.0007	0.1077	0.1239	0.6654
Polyommatus wagneri	0.1160	0.0541	0.0007	0.0903	0.1009	0.6380
Polyommatus zapvadi	0.1028	0.0487	0.0007	0.0924	0.1024	0.6531
Proterebia afer	0.1950	0.0837	0.0006	0.0680	0.0719	0.5809
Pseudochazara beroe	0.1020	0.0485	0.0007	0.0940	0.1054	0.6494
Pseudochazara lydia	0.2996	0.1177	0.0005	0.0493	0.0492	0.4837
Pseudochazara mamurra	0.1069	0.0505	0.0007	0.0931	0.1049	0.6438
Pseudochazara pelopea	0.2229	0.0916	0.0006	0.0675	0.0686	0.5488
Pseudochazara schakuhensis	0.2531	0.1052	0.0005	0.0531	0.0561	0.5320
Pseudochazara thelephassa	0.4458	0.1570	0.0003	0.0291	0.0270	0.3408
Pyrgus aladaghensis	0.1566	0.0701	0.0006	0.0748	0.0811	0.6169
Pyrgus bolkariensis	0.0672	0.0335	0.0007	0.1080	0.1216	0.6690
Pyrgus jupei	0.0293	0.0161	0.0007	0.1363	0.1597	0.6579
Satyrium abdominalis	0.2255	0.0923	0.0006	0.0674	0.0682	0.5460
Satyrium hyrcanicum	0.0562	0.0287	0.0007	0.1144	0.1302	0.6698
Satyrium marcidum	0.2531	0.1047	0.0005	0.0541	0.0567	0.5309
Satyrium myrtale	0.0646	0.0325	0.0007	0.1095	0.1253	0.6674
Satyrium zabni	0.3317	0.1282	0.0004	0.0431	0.0430	0.4535
Satyrus amasinus	0.1287	0.0591	0.0006	0.0844	0.0926	0.6346
Satyrus favonius	0.1096	0.0515	0.0007	0.0912	0.1015	0.6454
Satyrus iranicus	0.1142	0.0533	0.0006	0.0882	0.0972	0.6465
Satyrus parthicus	0.0709	0.0352	0.0007	0.1061	0.1198	0.6673
Spialia osthelderi	0.2978	0.1201	0.0004	0.0455	0.0474	0.4888
Thaleropis ionia	0.1534	0.0685	0.0006	0.0785	0.0849	0.6141
Thymelicus novus	0.2426	0.1004	0.0005	0.0575	0.0598	0.5391
Tomares callimachus	0.1713	0.0756	0.0006	0.0715	0.0770	0.6041
Tomares desinens	0.1078	0.0507	0.0006	0.0903	0.0996	0.6510
Tomares nesimachus	0.2132	0.0903	0.0005	0.0633	0.0667	0.5660
Tomares romanovi	0.1683	0.0744	0.0006	0.0725	0.0782	0.6060

Turanana cytis	0.0690	0.0343	0.0007	0.1071	0.1206	0.6683
Turanana endymion	0.1731	0.0751	0.0007	0.0771	0.0819	0.5922
Turanana taygetica	0.2457	0.1021	0.0005	0.0557	0.0584	0.5377
Zerynthia caucasica	0.1445	0.0654	0.0006	0.0786	0.0855	0.6255
Zerynthia deyrollei	0.2589	0.1028	0.0006	0.0610	0.0602	0.5165

Figure S4.1. Scatterplot showing the priority rank of a cell from the spatial prioritisation against the percentage of the cell covered by protected area sites, for each of the three different prioritisation approaches. Results for birds on the top row and butterflies on the bottom for prioritisations based on species distributions models for the current distribution of species

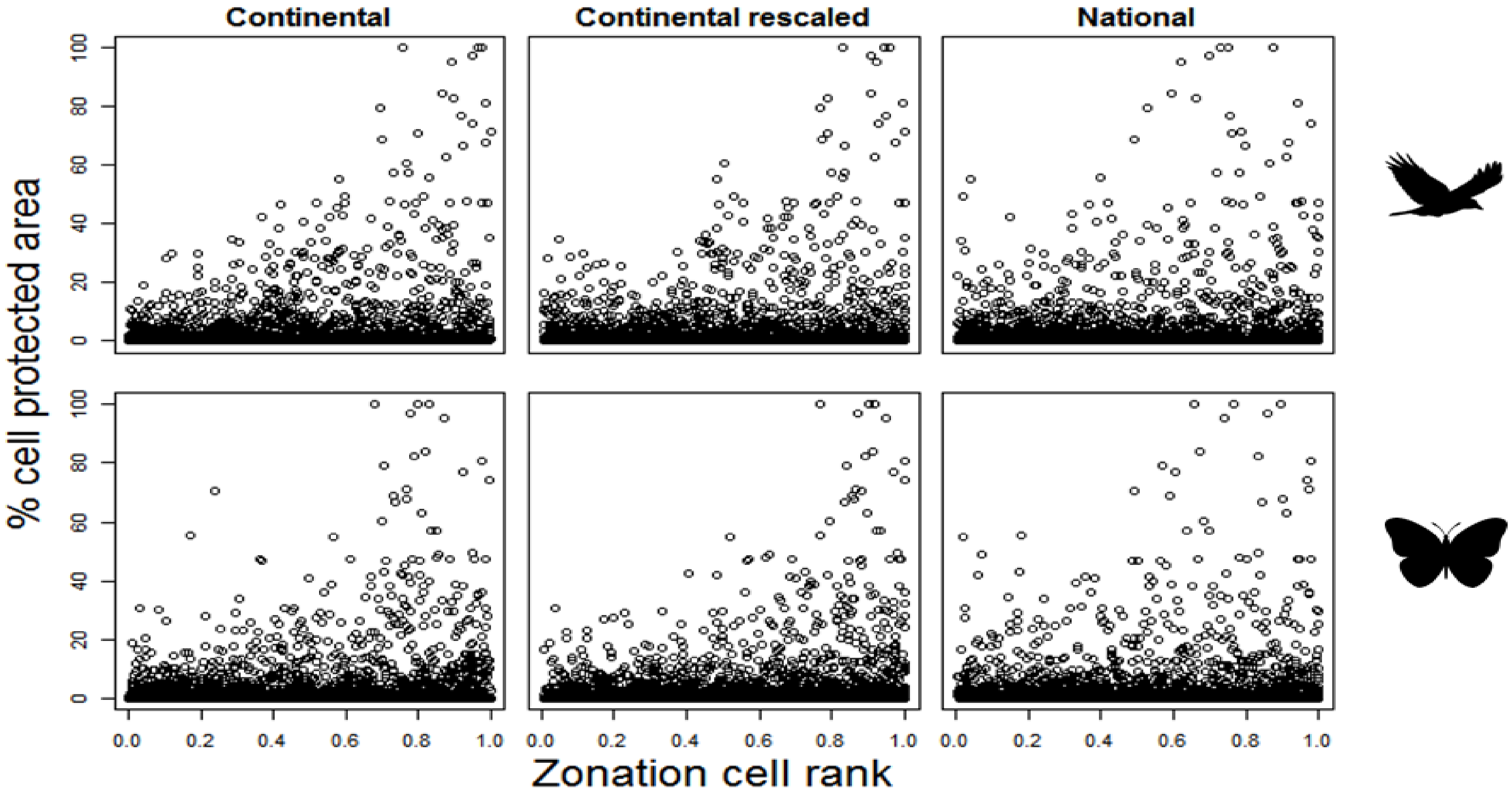
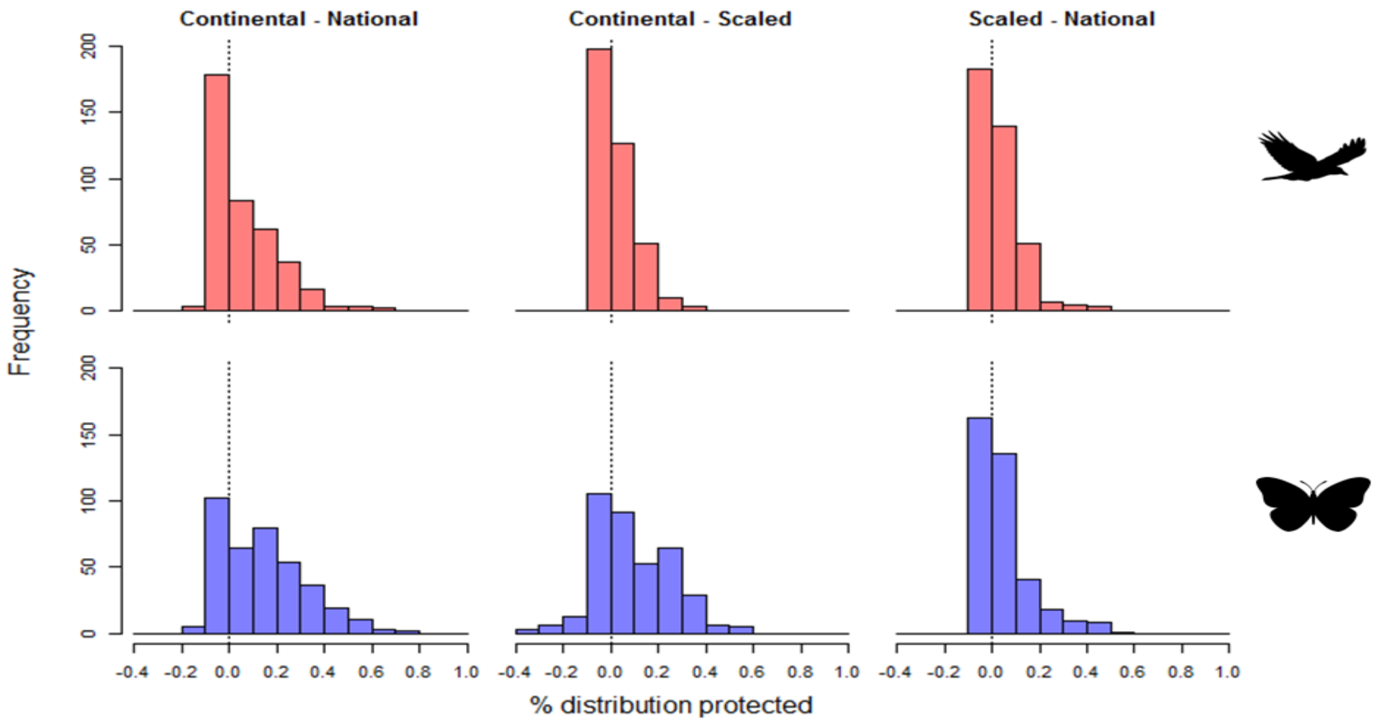


Figure S4.2. Differences in proportion of range protected for comparisons of each of the three prioritisation approaches at 17% of total landscape protection, birds on the top row and butterflies on the bottom. A positive difference shows the prioritisation approach listed first performed better for a species than the approach listed second in the comparison.



References

Akçakaya, H.R., Butchart, S.H.M., Watson, J.E.M. & Pearson, R.G. (2014). Preventing species extinctions resulting from climate change. *Nature Climate Change*, **4**, 1048–1049.

Angert, A.L., Crozier, L.G., Rissler, L.J., Gilman, S.E., Tewksbury, J.J. & Chunco, A.J. (2011). Do species' traits predict recent shifts at expanding range edges? *Ecology Letters*, **14**, 677–689.

Araújo, M.B., Cabeza, M., Thuiller, W., Hannah, L. & Williams, P.H. (2004). Would climate change drive species out of reserves? An assessment of existing reserve-selection methods. *Global Change Biology*, **10**, 1618–1626.

Araújo, M.B. & Guisan, A. (2006). Five (or so) challenges for species distribution modelling. *Journal of Biogeography*, **33**, 1677–1688.

Araújo, M.B. & Peterson, A.T. (2012). Uses and misuses of bioclimatic envelope modeling. *Ecology*, **93**, 1527–1539.

Araújo, M.B. & Rahbek, C. (2006). How does climate change affect biodiversity? *Science*, **313**, 1396–1397.

Araújo, M.B., Whittaker, R.J., Ladle, R.J. & Erhard, M. (2005). Reducing uncertainty in projections of extinction risk from climate change. *Global Ecology and Biogeography*, **14**, 529–538.

Arribas, P., Abellán, P., Velasco, J., Bilton, D.T., Millán, A. & Sánchez-Fernández, D. (2012). Evaluating drivers of vulnerability to climate change: a guide for insect conservation strategies. *Global Change Biology*, **18**, 2135–2146.

Asher, J., Warren, M.S., Fox, R., Harding, P., Jeffcoate, G. & Jeffcoate, S. (2001). *The millennium atlas of butterflies in Britain and Ireland*. Oxford University Press.

August, T., Powney, G., Harrower, C., Hill, M. & Isaac, N. (2015). sparta:

Trend Analysis for Unstructured Data.

Bagchi, R., Crosby, M., Huntley, B., Hole, D.G., Butchart, S.H.M., Collingham, Y., Kalra, M., Rajkumar, J., Rahmani, A., Pandey, M., Gurung, H., Trai, L.T., Van Quang, N. & Willis, S.G. (2013). Evaluating the effectiveness of conservation site networks under climate change: accounting for uncertainty. *Global Change Biology*, **19**, 1236–1248.

Balmer, D.E., Gillings, S., Caffrey, B., Swann, R.L., Downie, I.S. & Fuller, R.J. (2013). *Bird Atlas 2007-11: the breeding and wintering birds of Britain and Ireland*. BTO Thetford.

Balmford, A., Gaston, K.J., Rodrigues, A.S.L. & James, A. (2000). Integrating Costs of Conservation into International Priority Setting. *Conservation Biology*, **14**, 597–605.

Barnosky, A.D., Hadly, E.A., Bascompte, J., Berlow, E.L., Brown, J.H., Fortelius, M., Getz, W.M., Harte, J., Hastings, A., Marquet, P.A., Martinez, N.D., Mooers, A., Roopnarine, P., Vermeij, G., Williams, J.W., Gillespie, R., Kitzes, J., Marshall, C., Matzke, N., Mindell, D.P., Revilla, E. & Smith, A.B. (2012). Approaching a state shift in Earth's biosphere. *Nature*, **486**, 52–58.

Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O.U., Swartz, B., Quental, T.B., Marshall, C., McGuire, J.L., Lindsey, E.L., Maguire, K.C., Mersey, B. & Ferrer, E.A. (2011). Has the Earth's sixth mass extinction already arrived? *Nature*, **471**, 51–57.

Barrows, C.W., Hoines, J., Fleming, K.D., Vamstad, M.S., Murphy-Mariscal, M., Lalumiere, K. & Harding, M. (2014). Designing a sustainable monitoring framework for assessing impacts of climate change at Joshua Tree National Park, USA. *Biodiversity and Conservation*, **23**, 3263–3285.

Barton, J., Hine, R. & Pretty, J. (2009). The health benefits of walking in greenspaces of high natural and heritage value. *Journal of Integrative Environmental Sciences*, **6**, 261–278.

Batjes, N.H. (2005). *ISRIC-WISE global data set of derived soil properties on a 0.5 by 0.5 degree grid (ver. 3.0)*.

Beale, C.M., Baker, N.E., Brewer, M.J. & Lennon, J.J. (2013). Protected area networks and savannah bird biodiversity in the face of climate change and land degradation. *Ecology Letters*, **16**, 1061–1068.

Beale, C.M., Brewer, M.J. & Lennon, J.J. (2014). A new statistical framework for the quantification of covariate associations with species distributions. *Methods in Ecology and Evolution*, **5**, 421–432.

Beale, C.M. & Lennon, J.J. (2012). Incorporating uncertainty in predictive species distribution modelling. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **367**, 247–258.

Beckmann, B.C., Purse, B. V, Roy, D.B., Roy, H.E., Sutton, P.G. & Thomas, C.D. (2015). Two species with an unusual combination of traits dominate responses of British grasshoppers and crickets to environmental change. *PLoS ONE*, **10**, e0130488.

Beresford, A.E., Sanderson, F.J., Donald, P.F., Burfield, I.J., Butler, A., Vickery, J.A. & Buchanan, G.M. (2018). Phenology and climate change in Africa and the decline of Afro-Palearctic migratory bird populations. *Remote Sensing in Ecology and Conservation*.

Bertrand, R., Lenoir, J., Piedallu, C., Riofrio-Dillon, G., de Ruffray, P., Vidal, C., Pierrat, J.-C. & Gegout, J.-C. (2011). Changes in plant community composition lag behind climate warming in lowland forests. *Nature*, **479**, 517–520.

BirdLife International. (2004). *Birds in Europe: population estimates, trends and conservation status.* BirdLife International, Cambridge, U.K.

BirdLife International. (2015). *European Red List of Birds*. Office for Official Publications of the European Communities, Luxembourg.

BirdLife International. (2016). *IUCN Red List for Birds*. Office for Official Publications of the European Communities, Luxembourg.

BirdLife International & NatureServe. (2015). Bird species distribution maps of the world.

Both, C., Bouwhuis, S., Lessells, C.M. & Visser, M.E. (2006). Climate change and population declines in a long-distance migratory bird. *Nature*, **441**, 81–83.

Both, C., Van Turnhout, C.A.M., Bijlsma, R.G., Siepel, H., Van Strien, A.J. & Foppen, R.P.B. (2009). Avian population consequences of climate change are most severe for long-distance migrants in seasonal habitats. *Proceedings of the Royal Society of London B: Biological Sciences*.

Bottrill, M.C., Joseph, L.N., Carwardine, J., Bode, M., Cook, C., Game, E.T., Grantham, H., Kark, S., Linke, S., McDonald-Madden, E., Pressey, R.L., Walker, S., Wilson, K.A. & Possingham, H.P. (2008). Is conservation triage just smart decision making? *Trends in Ecology and Evolution*, **23**, 649–654.

Brambilla, M., Resano-Mayor, J., Scridel, D., Anderle, M., Bogliani, G., Braunisch, V., Capelli, F., Cortesi, M., Horrenberger, N., Pedrini, P., Sangalli, B., Chamberlain, D., Arlettaz, R. & Rubolini, D. (2018). Past and future impact of climate change on foraging habitat suitability in a high-alpine bird species: Management options to buffer against global warming effects. *Biological Conservation*, **221**, 209–218.

Brito, D., Ambal, R.G., Brooks, T., Silva, N. De, Foster, M., Hao, W., Hilton-Taylor, C., Paglia, A., Rodríguez, J.P. & Rodríguez, J.V. (2010). How similar are national red lists and the IUCN Red List? *Biological Conservation*, **143**, 1154–1158.

Brook, B.W., Sodhi, N.S. & Bradshaw, C.J.A. (2008). Synergies among extinction drivers under global change. *Trends in Ecology & Evolution*, **23**, 453–460.

Brooks, T.M., Mittermeier, R.A., da Fonseca, G.A.B., Gerlach, J., Hoffmann, M., Lamoreux, J.F., Mittermeier, C.G., Pilgrim, J.D. & Rodrigues, A.S.L. (2006). Global biodiversity conservation priorities. *Science*, **313**, 58–61.

Buckley, L.B. & Kingsolver, J.G. (2012). Functional and Phylogenetic Approaches to Forecasting Species' Responses to Climate Change. *Annual Review of Ecology, Evolution, and Systematics*, **43**, 205–226.

Bull, J.W., Gordon, A., Law, E.A., Suttle, K.B. & Milner-Gulland, E.J. (2014). Importance of baseline specification in evaluating conservation interventions and achieving no net loss of biodiversity. *Conservation Biology*, **28**, 799–809.

Burns, F., Eaton, M.A., Barlow, K.E., Beckmann, B.C., Brereton, T., Brooks, D.R., Brown, P.M.J., Al Fulaij, N., Gent, T., Henderson, I., Noble, D.G., Parsons, M., Powney, G.D., Roy, H.E., Stroh, P., Walker, K., Wilkinson, J.W., Wotton, S.R. & Gregory, R.D. (2016). Agricultural management and climatic change are the major drivers of biodiversity change in the UK. *PLoS ONE*, **11**, e0151595.

Butchart, S.H.M., Clarke, M., Smith, R.J., Sykes, R.E., Scharlemann, J.P.W., Harfoot, M., Buchanan, G.M., Angulo, A., Balmford, A., Bertzky, B., Brooks, T.M., Carpenter, K.E., Comeros-Raynal, M.T., Cornell, J., Ficetola, G.F., Fishpool, L.D.C., Fuller, R.A., Geldmann, J., Harwell, H., Hilton-Taylor, C., Hoffmann, M., Joolia, A., Joppa, L., Kingston, N., May, I., Milam, A., Polidoro, B., Ralph, G., Richman, N., Rondinini, C., Segan, D.B., Skolnik, B., Spalding, M.D., Stuart, S.N., Symes, A., Taylor, J., Visconti, P., Watson, J.E.M., Wood, L. & Burgess, N.D. (2015). Shortfalls and Solutions for Meeting National and Global Conservation Area Targets. *Conservation Letters*, **8**, 329–337.

Butchart, S.H.M., Scharlemann, J.P.W., Evans, M.I., Quader, S., Aricò, S., Arinaitwe, J., Balman, M., Bennun, L.A., Bertzky, B., Besançon, C., Boucher, T.M., Brooks, T.M., Burfield, I.J., Burgess, N.D., Chan, S., Clay, R.P., Crosby, M.J., Davidson, N.C., de Silva, N., Devenish, C., Dutson, G.C.L., Fernández, D.F.D., Fishpool, L.D.C., Fitzgerald, C., Foster, M., Heath, M.F., Hockings, M., Hoffmann, M., Knox, D., Larsen, F.W., Lamoreux, J.F., Loucks, C., May, I., Millett, J., Molloy, D., Morling, P., Parr, M., Ricketts, T.H., Seddon, N., Skolnik, B., Stuart, S.N., Upgren, A. & Woodley, S. (2012). Protecting important sites for biodiversity contributes to meeting global conservation targets. *PLoS ONE*, **7**, e32529.

Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, J.E.M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G.M., Chanson, J., Chenery, A.M., Csirke, J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway, J.N., Genovesi, P., Gregory, R.D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M.A., McRae, L., Minasyan, A., Morcillo, M.H., Oldfield, T.E.E., Pauly, D., Quader, S., Revenga, C., Sauer, J.R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S.N., Symes, A., Tierney, M., Tyrrell, T.D., Vié, J.-C. & Watson, R. (2010). Global biodiversity: indicators of recent declines. *Science*, **328**, 1164–1168.

Byrt, T., Bishop, J. & Carlin, J.B. (1993). Bias, prevalence and kappa. *Journal of Clinical Epidemiology*, **46**, 423–429.

Cade, B.S. & Noon, B.R. (2003). A gentle introduction to quantile regression for ecologists. *Frontiers in Ecology and the Environment*, **1**, 412–420.

Capela Lourenço, T., Cruz, M.J., Dzebo, A., Carlsen, H., Dunn, M., Juhász-Horváth, L. & Pinter, L. (2018). Are European decision-makers preparing for high-end climate change? *Regional Environmental Change*, 1–14.

Cardillo, M., Mace, G.M., Jones, K.E., Bielby, J., Bininda-Emonds, O.R.P., Sechrest, W., Orme, C.D.L. & Purvis, A. (2005). Multiple causes of high extinction risk in large mammal species. *Science*, **309**, 1239–1241.

CBD. (2003). *Consideration of the results of the meeting on "2010 - the global biodiversity challenge."* Convention on Biological Diversity.

CBD. (2010). *The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets*. Convention on Biological Diversity.

Ceballos, G., Ehrlich, P.R., Barnosky, A.D., García, A., Pringle, R.M. & Palmer, T.M. (2015). Accelerated modern human-induced species losses: Entering the sixth mass extinction. *Science Advances*, **1**, e1400253.

Ceballos, G., Ehrlich, P.R. & Dirzo, R. (2017). Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. *Proceedings of the National Academy of Sciences*, **114**, E6089–E6096.

Chen, I.-C., Hill, J.K., Ohlemüller, R., Roy, D.B. & Thomas, C.D. (2011). Rapid range shifts of species associated with high levels of climate warming. *Science*, **333**, 1024–1026.

Chessman, B.C. (2013). Identifying species at risk from climate change: Traits predict the drought vulnerability of freshwater fishes. *Biological Conservation*, **160**, 40–49.

Chin, A., Kyne, P.M., Walker, T.I. & McAuley, R.B. (2010). An integrated risk assessment for climate change: analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef. *Global Change Biology*, **16**, 1936–1953.

Cliquet, A., Backes, C., Harris, J. & Howsam, P. (2009). Adaptation to Climate Change-Legal Challenges for Protected Areas. *Utrecht Law Review*, **5**, 158–175.

Collen, B., Dulvy, N.K., Gaston, K.J., Gärdenfors, U., Keith, D.A., Punt, A.E., Regan, H.M., Böhm, M., Hedges, S., Seddon, M., Butchart, S.H.M., Hilton-Taylor, C., Hoffmann, M., Bachman, S.P. & Akçakaya, H.R. (2016). Clarifying misconceptions of extinction risk assessment with the IUCN Red List. *Biology Letters*, **12**, 20150843.

Crick, H.Q.P. (2004). The impact of climate change on birds. *Ibis*, **146**, 48–56.

Crick, H.Q.P., Dudley, C., Glue, D.E. & Thomson, D.L. (1997). UK birds are laying eggs earlier. *Nature*, **388**, 526.

Culp, L.A., Cohen, E.B., Scarpignato, A.L., Thogmartin, W.E. & Marra, P.P.

(2017). Full annual cycle climate change vulnerability assessment for migratory birds. *Ecosphere*, **8**, e01565.

Davey, C.M., Chamberlain, D.E., Newson, S.E., Noble, D.G. & Johnston, A. (2012). Rise of the generalists: evidence for climate driven homogenization in avian communities. *Global Ecology and Biogeography*, **21**, 568–578.

Davidson, A.D., Shoemaker, K.T., Weinstein, B., Costa, G.C., Brooks, T.M., Ceballos, G., Radeloff, V.C., Rondinini, C. & Graham, C.H. (2017). Geography of current and future global mammal extinction risk. *PLoS ONE*, **12**, e0186934.

Dawson, T.P., Jackson, S.T., House, J.I., Prentice, I.C. & Mace, G.M. (2011). Beyond Predictions: Biodiversity Conservation in a Changing Climate. *Science*, **332**, 53–58.

Devictor, V., Julliard, R., Couvet, D. & Jiguet, F. (2008). Birds are tracking climate warming, but not fast enough. *Proceedings of the Royal Society of London B: Biological Sciences*, **275**, 2743–2748.

Devictor, V., van Swaay, C., Brereton, T., Brotons, L., Chamberlain, D., Heliola, J., Herrando, S., Julliard, R., Kuussaari, M., Lindstrom, A., Reif, J., Roy, D.B., Schweiger, O., Settele, J., Stefanescu, C., Van Strien, A., Van Turnhout, C., Vermouzek, Z., WallisDeVries, M., Wynhoff, I. & Jiguet, F. (2012). Differences in the climatic debts of birds and butterflies at a continental scale. *Nature Climate Change*, **2**, 121–124.

Dirzo, R. & Raven, P.H. (2003). Global state of biodiversity and loss. *Annual Review of Environment and Resources*, **28**, 137–167.

Do, T.H., Krott, M., Juerges, N. & Böcher, M. (2018). Red lists in conservation science-policy interfaces: A case study from Vietnam. *Biological Conservation*, **226**, 101–110.

Dudley, N. (2008). *Guidelines for Applying Protected Area Management Categories*. IUCN, Gland, Switzerland.

Engler, J.O., Stiels, D., Schidelko, K., Strubbe, D., Quillfeldt, P. & Brambilla, M. (2017). Avian SDMs: current state, challenges, and opportunities. *Journal of Avian Biology*, **48**, 1483–1504.

Estrada, A., Morales-Castilla, I., Caplat, P. & Early, R. (2016). Usefulness of Species Traits in Predicting Range Shifts. *Trends in Ecology & Evolution*, **31**, 190–203.

Foden, W.B., Butchart, S.H.M., Stuart, S.N., Vié, J.-C., Akçakaya, H.R., Angulo, A., DeVantier, L.M., Gutsche, A., Turak, E., Cao, L., Donner, S.D., Katariya, V., Bernard, R., Holland, R.A., Hughes, A.F., O'Hanlon, S.E., Garnett, S.T., Şekercioğlu, Ç.H. & Mace, G.M. (2013). Identifying the World's Most Climate Change Vulnerable Species: A Systematic Trait-Based Assessment of all Birds, Amphibians and Corals. *PLoS ONE*, **8**, e65427.

Foden, W.B., Mace, G., Vié, J.-C., Angulo, A., Butchart, S., DeVantier, L., Dublin, H., Gutsche, A., Stuart, S. & Turak, E. (2008). Species susceptibility to climate change impacts. In: *2008 Rev. IUCN Red List Threat. Species* (eds. Vié, J.-C., Hilton-Taylor, C. & Stuart, S.N.). IUCN Gland, Switzerland.

Foden, W.B., Midgley, G.F., Hughes, G., Bond, W.J., Thuiller, W., Hoffman, M.T., Kaleme, P., Underhill, L.G., Rebelo, A. & Hannah, L. (2007). A changing climate is eroding the geographical range of the Namib Desert tree Aloe through population declines and dispersal lags. *Diversity and Distributions*, **13**, 645–653.

Foden, W.B. & Young, B.E. (2016). *IUCN SSC Guidelines for Assessing Species' Vulnerability to Climate Change*. IUCN Species Survival Commission., Cambridge, UK and Gland, Switzerland.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N. & Snyder, P.K. (2005). Global Consequences of Land Use. *Science*, **309**, 570–574.

Forister, M.L. & Shapiro, A.M. (2003). Climatic trends and advancing spring flight of butterflies in lowland California. *Global Change Biology*, **9**, 1130–1135.

Fox, R., Brereton, T.M., Asher, J., Botham, M.S., Middlebrook, I., Roy, D.B. & Warren, M.S. (2011). *The State of the UK's Butterflies 2011*. Butterfly Conservation and the Centre for Ecology & Hydrology.

Frishkoff, L.O., Karp, D.S., Flanders, J.R., Zook, J., Hadly, E.A., Daily, G.C. & M'Gonigle, L.K. (2016). Climate change and habitat conversion favour the same species. *Ecology Letters*, **19**, 1081–1090.

Fuller, R.A., McDonald-Madden, E., Wilson, K.A., Carwardine, J., Grantham, H.S., Watson, J.E.M., Klein, C.J., Green, D.C. & Possingham, H.P. (2010). Replacing underperforming protected areas achieves better conservation outcomes. *Nature*, **466**, 365–367.

Garcia, R.A., Burgess, N.D., Cabeza, M., Rahbek, C. & Araújo, M.B. (2012). Exploring consensus in 21st century projections of climatically suitable areas for African vertebrates. *Global Change Biology*, **18**, 1253–1269.

Gardali, T., Seavy, N.E., DiGaudio, R.T. & Comrack, L.A. (2012). A Climate Change Vulnerability Assessment of California's At-Risk Birds. *PLoS ONE*, **7**, e29507.

Gardenfors, U., Hilton-Taylor, C., Mace, G.M. & Rodríguez, J.P. (2001). The Application of IUCN Red List Criteria at. *Conservation Biology*, **15**, 1206–1212.

Garnett, S.T., Franklin, D.C., Ehmke, G., VanDerWal, J.J., Hodgson, L., Pavey, C., Reside, A.E., Welbergen, J.A., Butchart, S.H.M., Perkins, G.C. & Williams, S.E. (2013). *Climate change adaptation strategies for Australian birds*.

Geldmann, J., Barnes, M., Coad, L., Craigie, I.D., Hockings, M. & Burgess, N.D. (2013). Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. *Biological Conservation*, **161**, 230–238.

Gibbons, D.W., Reid, J.B. & Chapman, R.A. (1993). *The New Atlas of Breeding Birds in Britain and Ireland: 1988-1991*. T. & A.D. Poyser, London.

Gibbs, J.P. & Breisch, A.R. (2001). Climate Warming and Calling Phenology of Frogs near Ithaca, New York, 1900-1999. *Conservation Biology*, **15**, 1175–1178.

Gilbert, G., Brown, A.F. & Wotton, S.R. (2010). Current dynamics and predicted vulnerability to sea-level rise of a threatened Bittern Botaurus stellaris population. *Ibis*, **152**, 580–589.

Gilg, O., Sittler, B. & Hanski, I. (2009). Climate change and cyclic predator-prey population dynamics in the high Arctic. *Global Change Biology*, **15**, 2634–2652.

Gillingham, P.K., Bradbury, R.B., Roy, D.B., Anderson, B.J., Baxter, J.M., Bourn, N.A.D., Crick, H.Q.P., Findon, R.A., Fox, R., Franco, A., Hill, J.K., Hodgson, J.A., Holt, A.R., Morecroft, M.D., O'Hanlon, N.J., Oliver, T.H., Pearce-Higgins, J.W., Procter, D.A., Thomas, J.A., Walker, K.J., Walmsley, C.A., Wilson, R.J. & Thomas, C.D. (2015). The effectiveness of protected areas in the conservation of species with changing geographical ranges. *Biological Journal of the Linnean Society*, **115**, 707–717.

Gillings, S., Balmer, D.E. & Fuller, R.J. (2015). Directionality of recent bird distribution shifts and climate change in Great Britain. *Global Change Biology*, **21**, 2155–2168.

Gillson, L., Dawson, T.P., Jack, S. & McGeoch, M.A. (2013). Accommodating climate change contingencies in conservation strategy. *Trends in Ecology & Evolution*, **28**, 135–142.

De Grammont, P.C. & Cuarón, A.D. (2006). An Evaluation of Threatened Species Categorization Systems Used on the American Continent. *Conservation Biology*, **20**, 14–27.

Gratz, N.G. (1999). Emerging and resurging vector-borne diseases. *Annual*

Review of Entomology, **44**, 51–75.

Gray, C.L., Hill, S.L.L., Newbold, T., Hudson, L.N., Boïrger, L., Contu, S., Hoskins, A.J., Ferrier, S., Purvis, A. & Scharlemann, J.P.W. (2016). Local biodiversity is higher inside than outside terrestrial protected areas worldwide. *Nature Communications*, **7**, 12306.

Green, R.E., Collingham, Y.C., Willis, S.G., Gregory, R.D., Smith, K.W. & Huntley, B. (2008). Performance of climate envelope models in retrodicting recent changes in bird population size from observed climatic change. *Biology Letters*, **4**, 599–602.

Gregory, R.D., Van Strien, A., Vorisek, P., Meyling, A.W.G., Noble, D.G., Foppen, R.P.B. & Gibbons, D.W. (2005). Developing indicators for European birds. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **360**, 269–288.

Gregory, R.D., Willis, S.G., Jiguet, F., Voříšek, P., Klvaňová, A., van Strien, A., Huntley, B., Collingham, Y.C., Couvet, D. & Green, R.E. (2009). An Indicator of the Impact of Climatic Change on European Bird Populations. *PLoS ONE*, **4**, e4678.

Guisan, A. & Thuiller, W. (2005). Predicting species distribution: Offering more than simple habitat models. *Ecology Letters*, **8**, 993–1009.

Guo, F., Lenoir, J. & Bonebrake, T.C. (2018). Land-use change interacts with climate to determine elevational species redistribution. *Nature Communications*, **9**, 1315.

Hagemeijer, E.J.M. & Blair, M.J. (1997). *The EBCC Atlas of European Breeding Birds: their distribution and abundance*. T & A.D. Poyser, London.

Halpern, B.S., Pyke, C.R., Fox, H.E., Chris Haney, J., Schlaepfer, M.A. & Zaradic, P. (2006). Gaps and mismatches between global conservation priorities and spending. *Conservation Biology*, **20**, 56–64.

Hance, T., van Baaren, J., Vernon, P. & Boivin, G. (2007). Impact of Extreme

Temperatures on Parasitoids in a Climate Change Perspective. *Annual Review of Entomology*, **52**, 107–126.

Hanley, N., Czajkowski, M., Hanley-Nickolls, R. & Redpath, S. (2010). Economic values of species management options in human-wildlife conflicts: Hen Harriers in Scotland. *Ecological Economics*, **70**, 107–113.

Hannah, L., Flint, L., Syphard, A.D., Moritz, M.A., Buckley, L.B. & McCullough, I.M. (2014). Fine-grain modeling of species' response to climate change: Holdouts, stepping-stones, and microrefugia. *Trends in Ecology and Evolution*, **29**, 390–397.

Hannah, L., Midgley, G.F., Andelman, S., Araujo, M.B., Hughes, G., Martinez-Meyer, E., Pearson, R.G. & Williams, P.J. (2007). Protected area needs in a changing climate Advanced Search. *Frontiers in Ecology and the Environment*, **5**, 131–138.

Harper, A.B., Powell, T., Cox, P.M., House, J., Huntingford, C., Lenton, T.M., Sitch, S., Burke, E., Chadburn, S.E., Collins, W.J., Comyn-Platt, E., Daioglou, V., Doelman, J.C., Hayman, G., Robertson, E., van Vuuren, D., Wiltshire, A., Webber, C.P., Bastos, A., Boysen, L., Ciais, P., Devaraju, N., Jain, A.K., Krause, A., Poulter, B. & Shu, S. (2018). Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nature Communications*, **9**, 2938.

Harris, I., Jones, P.D., Osborn, T.J. & Lister, D.H. (2014). Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *International Journal of Climatology*, **34**, 623–642.

Harris, R.M.B., Beaumont, L.J., Vance, T.R., Tozer, C.R., Remenyi, T.A., Perkins-Kirkpatrick, S.E., Mitchell, P.J., Nicotra, A.B., McGregor, S., Andrew, N.R., Letnic, M., Kearney, M.R., Wernberg, T., Hutley, L.B., Chambers, L.E., Fletcher, M.-S., Keatley, M.R., Woodward, C.A., Williamson, G., Duke, N.C. & Bowman, D.M.J.S. (2018). Biological responses to the press and pulse of climate trends and extreme events. *Nature Climate Change*, **8**, 579–587.

Harvell, C.D., Mitchell, C.E., Ward, J.R., Altizer, S., Dobson, A.P., Ostfeld, R.S. & Samuel, M.D. (2002). Climate Warming and Disease Risks for Terrestrial and Marine Biota. *Science*, **296**, 2158–2162.

Hayhow, D.B., Bond, A.L., Eaton, M.A., Grice, P. V, Hall, C., Hall, J., Harris, S.J., Hearn, R.D., Holt, C.A., Noble, D.G., Stroud, D.A. & Wotton, S. (2015). *The state of the UK's birds 2015*.

Hegland, S.J., Nielsen, A., Lázaro, A., Bjerknes, A.-L. & Totland, Ø. (2009). How does climate warming affect plant-pollinator interactions? *Ecology Letters*, **12**, 184–195.

Heikkinen, R.K., Luoto, M., Leikola, N., Pöyry, J., Settele, J., Kudrna, O., Marmion, M., Fronzek, S. & Thuiller, W. (2010). Assessing the vulnerability of European butterflies to climate change using multiple criteria. *Biodiversity and Conservation*, **19**, 695–723.

Hickling, R., Roy, D.B., Hill, J.K., Fox, R. & Thomas, C.D. (2006). The distributions of a wide range of taxonomic groups are expanding polewards. *Global Change Biology*, **12**, 450–455.

Hijmans, R.J. (2016). raster: Geographic Data Analysis and Modeling.

Hiley, J.R., Bradbury, R.B., Holling, M. & Thomas, C.D. (2013). Protected areas act as establishment centres for species colonizing the UK. *Proceedings of the Royal Society B: Biological Sciences*, **280**, 20122310.

Hill, M.O. (2012). Local frequency as a key to interpreting species occurrence data when recording effort is not known. *Methods in Ecology and Evolution*, **3**, 195–205.

Hole, D.G., Willis, S.G., Pain, D.J., Fishpool, L.D., Butchart, S.H.M., Collingham, Y.C., Rahbek, C. & Huntley, B. (2009). Projected impacts of climate change on a continent-wide protected area network. *Ecology Letters*, **12**, 420–431.

Howard, C., Stephens, P.A., Pearce- Higgins, J.W., Gregory, R.D. & Willis, S.G. (2015). The drivers of avian abundance: patterns in the relative importance of climate and land use. *Global Ecology and Biogeography*, **24**, 1249–1260.

Howard, C., Stephens, P.A., Tobias, J.A., Sheard, C., Butchart, S.H.M. & Willis, S.G. (2018). Flight range, fuel load and the impact of climate change on the journeys of migrant birds. *Proceedings of the Royal Society B: Biological Sciences*, **285**, 20172329.

del Hoyo, J., Elliott, A., Sargatal, J., Christie, D.A. & de Juana, E. (2016). *Handbook of the Birds of the World Alive*. Lynx Edicions, Barcelona.

Huntingford, C. & Mercado, L.M. (2016). High chance that current atmospheric greenhouse concentrations commit to warmings greater than 1.5°C over land. *Scientific Reports*, **6**, 30294.

Huntley, B., Collingham, Y.C., Green, R.E., Hilton, G.M., Rahbek, C. & Willis, S.G. (2006). Potential impacts of climatic change upon geographical distributions of birds. *Ibis*, **148**, 8–28.

Huntley, B., Collingham, Y.C., Willis, S.G. & Green, R.E. (2008). Potential Impacts of Climatic Change on European Breeding Birds. *PLoS ONE*, **3**, e1439.

Inouye, D.W., Barr, B., Armitage, K.B. & Inouye, B.D. (2000). Climate change is affecting altitudinal migrants and hibernating species. *Proceedings of the National Academy of Sciences*, **97**, 1630–1633.

IPCC. (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. (2013). Summary for Policymakers. In: *Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang.* (eds. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P.M.). Cambridge University Press, Cambridge, United Kingdom and New

York, NY, USA.

IPCC. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

James, A.N., Gaston, K.J. & Balmford, A. (1999). Balancing the earth's accounts. *Nature*, **401**, 323–324.

Jetz, W., Wilcove, D.S. & Dobson, A.P. (2007). Projected Impacts of Climate and Land-Use Change on the Global Diversity of Birds. *PLoS Biology*, **5**, e157.

Johnson, C.N., Balmford, A., Brook, B.W., Buettel, J.C., Galetti, M., Guangchun, L. & Wilmshurst, J.M. (2017). Biodiversity losses and conservation responses in the Anthropocene. *Science*, **356**, 270–275.

Johnston, A., Ausden, M., Dodd, A.M., Bradbury, R.B., Chamberlain, D.E., Jiguet, F., Thomas, C.D., Cook, A.S.C.P., Newson, S.E., Ockendon, N., Rehfisch, M.M., Roos, S., Thaxter, C.B., Brown, A., Crick, H.Q.P., Douse, A., McCall, R.A., Pontier, H., Stroud, D.A., Cadiou, B., Crowe, O., Deceuninck, B., Hornman, M. & Pearce-Higgins, J.W. (2013). Observed and predicted effects of climate change on species abundance in protected areas. *Nature Climate Change*, **3**, 1055–1061.

Keith, D.A., Mahony, M., Hines, H., Elith, J., Regan, T.J., Baumgartner, J.B., Hunter, D., Heard, G.W., Mitchell, N.J., Parris, K.M., Penman, T., Scheele, B.E.N., Simpson, C.C., Tingley, R., Tracy, C.R., West, M. & Akçakaya, H.R. (2014). Detecting Extinction Risk from Climate Change by IUCN Red List Criteria. *Conservation Biology*, **28**, 810–819.

Keller, V. & Bollmann, K. (2004). From red lists to species of conservation concern. *Conservation Biology*, **18**, 1636–1644.

Kudrna, O., Harpke, A., Lux, K., Pennerstorfer, J., Schweiger, O., Settele, J. & Wiemers, M. (2011). *Distribution atlas of butterflies in Europe*.

Gesellschaft für Schmetterlingsschutz eV Halle.

Kukkala, A.S. & Moilanen, A. (2013). Core concepts of spatial prioritisation in systematic conservation planning. *Biological Reviews*, **88**, 443–464.

Kukkala, A.S., Santangeli, A., Butchart, S.H.M., Maiorano, L., Ramirez, I., Burfield, I.J. & Moilanen, A. (2016). Coverage of vertebrate species distributions by Important Bird and Biodiversity Areas and Special Protection Areas in the European Union. *Biological Conservation*, **202**, 1–9.

Larsen, F.W., Bladt, J., Balmford, A. & Rahbek, C. (2012). Birds as biodiversity surrogates: Will supplementing birds with other taxa improve effectiveness? *Journal of Applied Ecology*, **49**, 349–356.

Lehtomäki, J. & Moilanen, A. (2013). Methods and workflow for spatial conservation prioritization using Zonation. *Environmental Modelling & Software*, **47**, 128–137.

Lempert, R., Nakicenovic, N., Sarewitz, D. & Schlesinger, M. (2004). Characterizing climate-change uncertainties for decision-makers. An editorial essay. *Climatic Change*, **65**, 1–9.

Liao, J., Ying, Z., Hiebeler, D.E., Wang, Y., Takada, T. & Nijs, I. (2015). Species extinction thresholds in the face of spatially correlated periodic disturbance. *Scientific Reports*, **5**, 15455.

Lin, Y.-P., Lin, W.-C., Anthony, J., Ding, T.-S., Mihoub, J.-B., Henle, K. & Schmeller, D.S. (2018). Assessing uncertainty and performance of ensemble conservation planning strategies. *Landscape and Urban Planning*, **169**, 57–69.

Mace, G.M., Balmford, A., Boitani, L., Cowlishaw, G., Dobson, A.P., Faith, D.P., Gaston, K.J., Humphries, C.J., Vane-Wright, R.I., Williams, P.H., Lawton, J.H., Margules, C.R., May, R.M., Nicholls, A.O., Possingham, H.P., Rahbek, C. & van Jaarsveld, A.S. (2000). It’s time to work together and stop duplicating conservation efforts …. *Nature*, **405**, 393–393.

Mace, G.M., Collar, N.J., Gaston, K.J., Hilton-Taylor, C., Akçakaya, H.R., Leader-Williams, N., Milner-Gulland, E.J. & Stuart, S.N. (2008). Quantification of Extinction Risk: IUCN's System for Classifying Threatened Species. *Conservation Biology*, **22**, 1424–1442.

Mace, G.M., Cramer, W., Díaz, S., Faith, D.P., Larigauderie, A., Le Prestre, P., Palmer, M., Perrings, C., Scholes, R.J., Walpole, M., Walther, B.A., Watson, J.E.M. & Mooney, H.A. (2010). Biodiversity targets after 2010. *Current Opinion in Environmental Sustainability*, **2**, 3–8.

Maciejewski, K. & Kerley, G.I.H. (2014). Understanding tourists' preference for mammal species in private protected areas: Is there a case for extralimital species for ecotourism? *PLoS ONE*, **9**, e88192.

Maclean, I.M.D., Suggitt, A.J., Wilson, R.J., Duffy, J.P. & Bennie, J.J. (2017). Fine-scale climate change: modelling spatial variation in biologically meaningful rates of warming. *Global Change Biology*, **23**, 256–268.

Maclean, I.M.D. & Wilson, R.J. (2011). Recent ecological responses to climate change support predictions of high extinction risk. *Proceedings of the National Academy of Sciences*, **108**, 12337–12342.

MacLean, S.A. & Beissinger, S.R. (2017). Species' traits as predictors of range shifts under contemporary climate change: a review and meta-analysis. *Global Change Biology*, **23**, 4094–4105.

Mair, L., Hill, J.K., Fox, R., Botham, M., Brereton, T. & Thomas, C.D. (2014). Abundance changes and habitat availability drive species/' responses to climate change. *Nature Climate Change*, **4**, 127–131.

Di Marco, M., Collen, B., Rondinini, C. & Mace, G.M. (2015). Historical drivers of extinction risk: using past evidence to direct future monitoring. *Proceedings of the Royal Society of London B: Biological Sciences*, **282**, 20150928.

Margules, C.R. & Pressey, R.L. (2000). Systematic conservation planning. *Nature*, **405**, 243–253.

Martín-López, B., Montes, C., Ramírez, L. & Benayas, J. (2009). What drives policy decision-making related to species conservation? *Biological Conservation*, **142**, 1370–1380.

Martin, T.G., Nally, S., Burbidge, A.A., Arnall, S., Garnett, S.T., Hayward, M.W., Lumsden, L.F., Menkhorst, P., McDonald-Madden, E. & Possingham, H.P. (2012). Acting fast helps avoid extinction. *Conservation Letters*, **5**, 274–280.

Marton-Lefèvre, J. (2010). Biodiversity Is Our Life. *Science*, **327**, 1179.

Mason, S.C., Palmer, G., Fox, R., Gillings, S., Hill, J.K., Thomas, C.D. & Oliver, T.H. (2015). Geographical range margins of many taxonomic groups continue to shift polewards. *Biological Journal of the Linnean Society*, **115**, 586–597.

Massimino, D., Johnston, A. & Pearce-Higgins, J.W. (2015). The geographical range of British birds expands during 15 years of warming. *Bird Study*, **62**, 523–534.

McHugh, M.L. (2012). Interrater reliability: the kappa statistic. *Biochemia Medica*, **22**, 276–282.

McKinney, M.L. (1997). How do rare species avoid extinction? A paleontological view. In: *Biol. Rarity*, Population and Community Biology Series (eds. Kunin, W.E. & Gaston, K.J.). Springer Netherlands, pp. 110–129.

McKinney, M.L. (1999). High rates of extinction and threat in poorly studied taxa. *Conservation Biology*, **13**, 1273–1281.

Memmott, J., Craze, P.G., Waser, N.M. & Price, M. V. (2007). Global warming and the disruption of plant-pollinator interactions. *Ecology Letters*, **10**, 710–717.

Meng, H., Carr, J., Beraducci, J., Bowles, P., Branch, W.R., Capitani, C., Chenga, J., Cox, N., Howell, K., Malonza, P., Marchant, R., Mbilinyi, B., Mukama, K., Msuya, C., Platts, P.J., Safari, I., Spawls, S., Shennan-

Farpon, Y., Wagner, P. & Burgess, N.D. (2016). Tanzania’s reptile biodiversity: Distribution, threats and climate change vulnerability. *Biological Conservation*, **204**, 72–82.

Menzel, A. & Fabian, P. (1999). Growing season extended in Europe. *Nature*, **397**, 659–659.

Menzel, A., Sparks, T.H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kübler, K., Bissolli, P., Braslavská, O., Briede, A., Chmielewski, F.M., Crepinsek, Z., Curnel, Y., Dahl, Å., Defila, C., Donnelly, A., Filella, Y., Jatczak, K., Måge, F., Mestre, A., Nordli, Ø., Peñuelas, J., Pirinen, P., Remišová, V., Scheifinger, H., Striz, M., Susnik, A., Van Vliet, A.J.H., Wielgolaski, F.-E., Zach, S. & Zust, A. (2006). European phenological response to climate change matches the warming pattern. *Global Change Biology*, **12**, 1969–1976.

Moilanen, A. & Arponen, A. (2011). Administrative regions in conservation: Balancing local priorities with regional to global preferences in spatial planning. *Biological Conservation*, **144**, 1719–1725.

Moilanen, A., Franco, A.M.A., Early, R.I., Fox, R., Wintle, B. & Thomas, C.D. (2005). Prioritizing multiple-use landscapes for conservation: methods for large multi-species planning problems. *Proceedings of the Royal Society B: Biological Sciences*, **272**, 1885–1891.

Moller, A.P., Rubolini, D. & Lehikoinen, E. (2008). Populations of migratory bird species that did not show a phenological response to climate change are declining. *Proceedings of the National Academy of Sciences*, **105**, 16195–16200.

Montesino Pouzols, F., Toivonen, T., Di Minin, E., Kukkala, A.S., Kullberg, P., Kuustera, J., Lehtomaki, J., Tenkanen, H., Verburg, P.H. & Moilanen, A. (2014). Global protected area expansion is compromised by projected land-use and parochialism. *Nature*, **516**, 383–386.

Mora, C., Frazier, A.G., Longman, R.J., Dacks, R.S., Walton, M.M., Tong, E.J., Sanchez, J.J., Kaiser, L.R., Stender, Y.O., Anderson, J.M., Ambrosino, C.M., Fernandez-Silva, I., Giuseffi, L.M. & Giambelluca, T.W. (2013). The projected timing of climate departure from recent variability. *Nature*, **502**, 183–187.

Mora, C., Tittensor, D.P., Adl, S., Simpson, A.G.B. & Worm, B. (2011). How Many Species Are There on Earth and in the Ocean? *PLoS Biology*, **9**, e1001127.

Moyle, P.B., Kiernan, J.D., Crain, P.K. & Quiñones, R.M. (2013). Climate Change Vulnerability of Native and Alien Freshwater Fishes of California: A Systematic Assessment Approach. *PLoS ONE*, **8**, e63883.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B. & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, **403**, 853–858.

Navarro, L.M. & Pereira, H.M. (2015). Rewilding abandoned landscapes in Europe. In: *Rewilding Eur. Landscapes*. Springer International Publishing, Cham, pp. 3–23.

Newbold, T. (2018). Future effects of climate and land-use change on terrestrial vertebrate community diversity under different scenarios. *Proceedings of the Royal Society B: Biological Sciences*, **285**, 20180792.

Newton, I. (2004). Population limitation in migrants. *Ibis*, **146**, 197–226.

Nicholson, E., Regan, T.J., Auld, T.D., Burns, E.L., Chisholm, L.A., English, V., Harris, S., Harrison, P., Kingsford, R.T., Leishman, M.R., Metcalfe, D.J., Pisanu, P., Watson, C.J., White, M., White, M.D., Williams, R.J., Wilson, B. & Keith, D.A. (2015). Towards consistency, rigour and compatibility of risk assessments for ecosystems and ecological communities. *Austral Ecology*, **40**, 347–363.

Oliver, T.H., Gillings, S., Pearce-Higgins, J.W., Brereton, T., Crick, H.Q.P., Duffield, S.J., Morecroft, M.D. & Roy, D.B. (2017). Large extents of intensive land use limit community reorganization during climate warming. *Global Change Biology*, **23**, 2272–2283.

Osborn, T.J. (2009). A user guide for ClimGen: a flexible tool for generating monthly climate data sets and scenarios.

Pacifici, M., Foden, W.B., Visconti, P., Watson, J.E.M., Butchart, S.H.M., Kovacs, K.M., Scheffers, B.R., Hole, D.G., Martin, T.G., Akçakaya, H.R., Corlett, R.T., Huntley, B., Bickford, D., Carr, J.A., Hoffmann, A.A., Midgley, G.F., Pearce-Kelly, P., Pearson, R.G., Williams, S.E., Willis, S.G., Young, B. & Rondinini, C. (2015). Assessing species vulnerability to climate change. *Nature Climate Change*, **5**, 215–224.

Pacifici, M., Visconti, P., Butchart, S.H.M., Watson, J.E.M., Cassola, F.M. & Rondinini, C. (2017). Species' traits influenced their response to recent climate change. *Nature Climate Change*, **7**, 205–208.

Pack, S.M., Ferreira, M.N., Krithivasan, R., Murrow, J., Bernard, E. & Mascia, M.B. (2016). Protected Area Downgrading, Downsizing, and Degazettement (PADDD) in the Amazon. *Biological Conservation*, **197**, 32–39.

Papworth, S.K., Rist, J., Coad, L. & Milner-Gulland, E.J. (2009). Evidence for shifting baseline syndrome in conservation. *Conservation Letters*, **2**, 93–100.

Parmesan, C. (2006). Ecological and Evolutionary Responses to Recent Climate Change. *Annual Review of Ecology, Evolution, and Systematics*, **37**, 637–669.

Parmesan, C. & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, **421**, 37–42.

Pearce-Higgins, J.W., Ausden, M.A., Beale, C.M., Oliver, T.H. & Crick, H.Q.P. (2015a). *Research on the assessment of risks & opportunities for species in England as a result of climate change*. Natural England Commissioned Reports, Number 175.

Pearce-Higgins, J.W., Eglington, S.M., Martay, B. & Chamberlain, D.E. (2015b). Drivers of climate change impacts on bird communities. *Journal of Animal Ecology*, **84**, 943–954.

Pearson, R.G., Stanton, J.C., Shoemaker, K.T., Aiello-Lammens, M.E., Ersts, P.J., Horning, N., Fordham, D.A., Raxworthy, C.J., Ryu, H.Y., McNees, J. & Akçakaya, H.R. (2014). Life history and spatial traits predict extinction risk due to climate change. *Nature Climate Change*, **4**, 217–221.

Pereira, H.M., Leadley, P.W., Proença, V., Alkemade, R., Scharlemann, J.P.W., Fernandez-Manjarrés, J.F., Araújo, M.B., Balvanera, P., Biggs, R., Cheung, W.W.L., Chini, L., Cooper, H.D., Gilman, E.L., Guénette, S., Hurtt, G.C., Huntington, H.P., Mace, G.M., Oberdorff, T., Revenga, C., Rodrigues, P., Scholes, R.J., Sumaila, U.R. & Walpole, M. (2010). Scenarios for Global Biodiversity in the 21st Century. *Science*, **330**, 1496–1501.

Peters, G.P., Andrew, R.M., Canadell, J.G., Fuss, S., Jackson, R.B., Korsbakken, J.I., Le Quéré, C. & Nakicenovic, N. (2017). Key indicators to track current progress and future ambition of the Paris Agreement. *Nature Climate Change*, **7**, 118–122.

Pimm, S.L., Jenkins, C.N., Abell, R., Brooks, T.M., Gittleman, J.L., Joppa, L.N., Raven, P.H., Roberts, C.M. & Sexton, J.O. (2014). The biodiversity of species and their rates of extinction, distribution, and protection. *Science*, **344**, 1246752.

Pimm, S.L., Raven, P., Peterson, A., Şekercioğlu, Ç.H. & Ehrlich, P.R. (2006). Human impacts on the rates of recent, present, and future bird extinctions. *Proceedings of the National Academy of Sciences*, **103**, 10941–10946.

Pimm, S.L., Russell, G.J., Gittleman, J.L. & Brooks, T.M. (1995). The future of biodiversity. *Science*, **269**, 347–349.

Pitman, N.C.A. & Jørgensen, P.M. (2002). Estimating the Size of the World's Threatened Flora. *Science*, **298**, 989.

Popov, I., Fadeeva, A., Palenova, E., Shamilishvily, G., Gorin, K., Burdo, A., Melchakova, E., Trofimova, Y., Sukristik, V., Morova, N., Kroo, K. &

Kirillova, Y. (2017). Effectiveness of “The IUCN red list of threatened species” application on a regional scale: current state of the “Red Data books” of Russia. *Biological Communications*, **62**, 57–60.

Pounds, J.A., Bustamante, M.R., Coloma, L.A., Consuegra, J.A., Fogden, M.P.L., Foster, P.N., La Marca, E., Masters, K.L., Merino-Viteri, A., Puschendorf, R., Ron, S.R., Sánchez-Azofeifa, G.A., Still, C.J. & Young, B.E. (2006). Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature*, **439**, 161–167.

Pressey, R.L., Cabeza, M., Watts, M.E., Cowling, R.M. & Wilson, K.A. (2007). Conservation planning in a changing world. *Trends in Ecology and Evolution*, **22**, 583–592.

R Core Team. (2016). R: A Language and Environment for Statistical Computing.

Rands, M.R.W., Adams, W.M., Bennun, L., Butchart, S.H.M., Clements, A., Coomes, D., Entwistle, A., Hodge, I., Kapos, V., Scharlemann, J.P.W., Sutherland, W.J. & Vira, B. (2010). Biodiversity conservation: Challenges beyond 2010. *Science*, **329**, 1298–1303.

Rempel, R.S. & Hornseth, M.L. (2017). Binational climate change vulnerability assessment of migratory birds in the Great Lakes Basins: Tools and impediments. *PLOS ONE*, **12**, 1–17.

Reside, A.E., VanDerWal, J. & Moran, C. (2017). Trade-offs in carbon storage and biodiversity conservation under climate change reveal risk to endemic species. *Biological Conservation*, **207**, 9–16.

Roberge, J.-M. & Angelstam, P. (2004). Usefulness of the Umbrella Species Concept as a Conservation Tool. *Conservation Biology*, **18**, 76–85.

Rodrigues, A.S.L., Pilgrim, J.D., Lamoreux, J.F., Hoffmann, M. & Brooks, T.M. (2006). The value of the IUCN Red List for conservation. *Trends in Ecology & Evolution*, **21**, 71–76.

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K. & Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °c. *Nature*, **534**, 631–639.

Root, T.L., Price, J.T., Hall, K.R., Schneider, S.H., Rosenzweig, C. & Pounds, J.A. (2003). Fingerprints of global warming on wild animals and plants. *Nature*, **421**, 57–60.

Roy, D.B. & Sparks, T.H. (2000). Phenology of British butterflies and climate change. *Global Change Biology*, **6**, 407–416.

Rull, V. (2009). Microrefugia. *Journal of Biogeography*, **36**, 481–484.

Sanford, T., Frumhoff, P.C., Luers, A. & Gulledge, J. (2014). The climate policy narrative for a dangerously warming world. *Nature Climate Change*, **4**, 164–166.

Scheffers, B.R., De Meester, L., Bridge, T.C.L., Hoffmann, A.A., Pandolfi, J.M., Corlett, R.T., Butchart, S.H.M., Pearce-Kelly, P., Kovacs, K.M., Dudgeon, D., Pacifici, M., Rondinini, C., Foden, W.B., Martin, T.G., Mora, C., Bickford, D. & Watson, J.E.M. (2016). The broad footprint of climate change from genes to biomes to people. *Science*, **354**.

Şekercioğlu, Ç.H., Schneider, S.H., Fay, J.P. & Loarie, S.R. (2008). Climate change, elevational range shifts, and bird extinctions. *Conservation Biology*, **22**, 140–150.

Semper-Pascual, A., Macchi, L., Sabatini, F.M., Decarre, J., Baumann, M., Blendinger, P.G., Gómez-Valencia, B., Mastrangelo, M.E. & Kuemmerle, T. (2018). Mapping extinction debt highlights conservation opportunities for birds and mammals in the South American Chaco. *Journal of Applied Ecology*, **55**, 1218–1229.

Settele, J., Kudrna, O., Harpke, A., Kühn, I., Van Swaay, C., Verovnik, R., Warren, M.S., Wiemers, M., Hanspach, J., Hickler, T. & Others. (2008). *Climatic risk atlas of European butterflies*. Pensoft Sofia-Moscow.

Sherry, R.A., Zhou, X., Gu, S., Arnone, J.A., Schimel, D.S., Verburg, P.S., Wallace, L.L. & Luo, Y. (2007). Divergence of reproductive phenology under climate warming. *Proceedings of the National Academy of Sciences*, **104**, 198–202.

Shoo, L.P., Hoffmann, A.A., Garnett, S., Pressey, R.L., Williams, Y.M., Taylor, M., Falconi, L., Yates, C.J., Scott, J.K., Alagador, D. & Williams, S.E. (2013). Making decisions to conserve species under climate change. *Climatic Change*, **119**, 239–246.

Small-Lorenz, S.L., Culp, L.A., Ryder, T.B., Will, T.C. & Marra, P.P. (2013). A blind spot in climate change vulnerability assessments. *Nature Climate Change*, **3**, 91–93.

Smith, K.F., Sax, D.F. & Lafferty, K.D. (2006). Evidence for the Role of Infectious Disease in Species Extinction and Endangerment. *Conservation Biology*, **20**, 1349–1357.

Sofaer, H.R., Jarnevich, C.S. & Flather, C.H. (2018). Misleading prioritizations from modelling range shifts under climate change. *Global Ecology and Biogeography*, **27**, 658–666.

La Sorte, F.A. & Jetz, W. (2012). Tracking of climatic niche boundaries under recent climate change. *Journal of Animal Ecology*, **81**, 914–925.

Stephens, P.A., Mason, L.R., Green, R.E., Gregory, R.D., Sauer, J.R., Alison, J., Aunins, A., Brotons, L., Butchart, S.H.M., Campedelli, T., Chodkiewicz, T., Chylarecki, P., Crowe, O., Elts, J., Escandell, V., Foppen, R.P.B., Heldbjerg, H., Herrando, S., Husby, M., Jiguet, F., Lehikoinen, A., Lindström, Å., Noble, D.G., Paquet, J.-Y., Reif, J., Sattler, T., Szép, T., Teufelbauer, N., Trautmann, S., van Strien, A.J., van Turnhout, C.A.M., Vorisek, P. & Willis, S.G. (2016). Consistent response of bird populations to climate change on two continents. *Science*, **352**, 84–87.

Suggitt, A.J., Wilson, R.J., Isaac, N.J.B., Beale, C.M., Auffret, A.G., August, T., Bennie, J.J., Crick, H.Q.P., Duffield, S., Fox, R., Hopkins, J.J., Macgregor, N.A., Morecroft, M.D., Walker, K.J. & Maclean, I.M.D.

(2018). Extinction risk from climate change is reduced by microclimatic buffering. *Nature Climate Change*, **8**, 713–717.

van Swaay, C., Cuttelod, A., Collins, S., Maes, D., López Munguira, M., Šašić, M., Settele, J., Verovnik, R., Verstrael, T., Warren, M., Wiemers, M. & Wynhof, I. (2010). *European Red List of Butterfies*. Publications Office of the European Union., Luxembourg.

van Swaay, C., Wynhoff, I., Wiemers, M., Katbeh-Bader, A., Power, A., Benyamini, D., Tzirkalli, E., Balletto, E., Monteiro, E., Karaçetin, E., Franeta, F., Pe'er, G., Welch, H., Thompson, K., Pamperis, L., Dapporto, L., Šašić, M., López Munguira, M., Micevski, N., Dupont, P., Garcia-Pereira, P., Moulai, R., Caruana, R., Verovnik, R., Bonelli, S. & Beshkov, S. (2016). *The IUCN Red List of Threatened Species*. Publications Office of the European Union., Luxembourg.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., de Siqueira, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huerta, M.A., Townsend Peterson, A., Phillips, O.L. & Williams, S.E. (2004a). Extinction risk from climate change. *Nature*, **427**, 145–148.

Thomas, C.D. & Gillingham, P.K. (2015). The performance of protected areas for biodiversity under climate change. *Biological Journal of the Linnean Society*, **115**, 718–730.

Thomas, C.D., Gillingham, P.K., Bradbury, R.B., Roy, D.B., Anderson, B.J., Baxter, J.M., Bourn, N.A.D., Crick, H.Q.P., Findon, R.A., Fox, R., Hodgson, J.A., Holt, A.R., Morecroft, M.D., O'Hanlon, N.J., Oliver, T.H., Pearce-Higgins, J.W., Procter, D.A., Thomas, J.A., Walker, K.J., Walmsley, C.A., Wilson, R.J. & Hill, J.K. (2012). Protected areas facilitate species' range expansions. *Proceedings of the National Academy of Sciences*, **109**, 14063–14068.

Thomas, C.D., Hill, J.K., Anderson, B.J., Bailey, S., Beale, C.M., Bradbury, R.B., Bulman, C.R., Crick, H.Q.P., Eigenbrod, F., Griffiths, H.M., Kunin, W.E., Oliver, T.H., Walmsley, C.A., Watts, K., Worsfold, N.T. & Yardley, T. (2011). A framework for assessing threats and benefits to species responding to climate change. *Methods in Ecology and Evolution*, **2**, 125–142.

Thomas, C.D. & Lennon, J.J. (1999). Birds extend their ranges northwards. *Nature*, **399**, 213.

Thomas, J.A., Telfer, M.G., Roy, D.B., Preston, C.D., Greenwood, J.J.D., Asher, J., Fox, R., Clarke, R.T. & Lawton, J.H. (2004b). Comparative Losses of British Butterflies, Birds, and Plants and the Global Extinction Crisis. *Science*, **303**, 1879–1881.

Tilman, D., May, R.M., Lehman, C.L. & Nowak, M.A. (1994). Habitat destruction and the extinction debt. *Nature*, **371**, 65–66.

Tittensor, D.P., Walpole, M., Hill, S.L.L., Boyce, D.G., Britten, G.L., Burgess, N.D., Butchart, S.H.M., Leadley, P.W., Regan, E.C., Alkemade, R., Baumung, R., Bellard, C., Bouwman, L., Bowles-Newark, N.J., Chenery, A.M., Cheung, W.W.L., Christensen, V., Cooper, H.D., Crowther, A.R., Dixon, M.J.R., Galli, A., Gaveau, V., Gregory, R.D., Gutierrez, N.L., Hirsch, T.L., Höft, R., Januchowski-Hartley, S.R., Karmann, M., Krug, C.B., Leverington, F.J., Loh, J., Lojenga, R.K., Malsch, K., Marques, A., Morgan, D.H.W., Mumby, P.J., Newbold, T., Noonan-Mooney, K., Pagad, S.N., Parks, B.C., Pereira, H.M., Robertson, T., Rondinini, C., Santini, L., Scharlemann, J.P.W., Schindler, S., Sumaila, U.R., Teh, L.S.L., van Kolck, J., Visconti, P. & Ye, Y. (2014). A mid-term analysis of progress toward international biodiversity targets. *Science*, **346**, 241–244.

Triviño, M., Cabeza, M., Thuiller, W., Hickler, T. & Araújo, M.B. (2013). Risk assessment for Iberian birds under global change. *Biological Conservation*, **168**, 192–200.

Trull, N., Böhm, M. & Carr, J. (2018). Patterns and biases of climate change threats in the IUCN Red List. *Conservation Biology*, **32**, 135–147.

Tshikolovets, V. V. (2011). *Butterflies of Europe & the Mediterranean area*. Tshikolovets publications.

UNEP-WCMC & IUCN. (2016). *Protected Planet Report 2016*. Cambridge UK and Gland, Switzerland.

UNFCC. (2015). *Adoption of the Paris Agreement*.

Urban, M.C. (2015). Accelerating extinction risk from climate change. *Science*, **348**, 571–573.

Venter, O., Fuller, R.A., Segan, D.B., Carwardine, J., Brooks, T., Butchart, S.H.M., Di Marco, M., Iwamura, T., Joseph, L., O'Grady, D., Possingham, H.P., Rondinini, C., Smith, R.J., Venter, M. & Watson, J.E.M. (2014). Targeting Global Protected Area Expansion for Imperiled Biodiversity. *PLoS Biology*, **12**, e1001891.

Vignoli, L., Macale, D., Luiselli, L., Lecis, R. & Casula, P. (2017). Are conservation assessments of threatened species reliable? Updated distribution of the Endangered Sardinian newt Euproctus platycephalus and implications for Red List assessments of Italian amphibians. *ORYX*, **51**, 482–488.

Visser, M.E. & Both, C. (2005). Shifts in phenology due to global climate change: the need for a yardstick. *Proceedings of the Royal Society of London B: Biological Sciences*, **272**, 2561–2569.

Wade, A.A., Hand, B.K., Kovach, R.P., Muhlfeld, C.C., Waples, R.S. & Luikart, G. (2016). Assessments of species' vulnerability to climate change: from pseudo to science. *Biodiversity and Conservation*, **26**, 1–7.

Wake, D.B. & Vredenburg, V.T. (2008). Are we in the midst of the sixth mass extinction? A view from the world of amphibians. *Proceedings of the National Academy of Sciences*, **105**, 11466–11473.

Walpole, M.J. & Leader-Williams, N. (2002). Tourism and flagship species in conservation. *Biodiversity and Conservation*, **11**, 543–547.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.-M., Hoegh-Guldberg, O. & Bairlein, F. (2002). Ecological responses to recent climate change. *Nature*, **416**, 389–395.

Warren, R., Price, J., Fischlin, A., de la Nava Santos, S. & Midgley, G. (2011). Increasing impacts of climate change upon ecosystems with increasing global mean temperature rise. *Climatic Change*, **106**, 141–177.

Warren, R., Price, J., Graham, E., Forstenhaeusler, N. & VanDerWal, J. (2018). The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. *Science*, **360**, 791–795.

Warren, R., VanDerWal, J., Price, J., Welbergen, J.A., Atkinson, I., Ramirez-Villegas, J., Osborn, T.J., Jarvis, A., Shoo, L.P., Williams, S.E. & Lowe, J. (2013). Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change*, **3**, 678–682.

Watson, J.E.M., Dudley, N., Segan, D.B. & Hockings, M. (2014). The performance and potential of protected areas. *Nature*, **515**, 67–73.

Watts, M.E., Ball, I.R., Stewart, R.S., Klein, C.J., Wilson, K., Steinback, C., Lourival, R., Kircher, L. & Possingham, H.P. (2009). Marxan with Zones: Software for optimal conservation based land- and sea-use zoning. *Environmental Modelling and Software*, **24**, 1513–1521.

Wheatley, C.J., Beale, C.M., Bradbury, R.B., Pearce-Higgins, J.W., Critchlow, R. & Thomas, C.D. (2017). Climate change vulnerability for species—Assessing the assessments. *Global Change Biology*, **23**, 3704–3715.

Williams, S.E., Shoo, L.P., Isaac, J.L., Hoffmann, A.A. & Langham, G. (2008). Towards an Integrated Framework for Assessing the Vulnerability of Species to Climate Change. *PLoS Biology*, **6**, e325.

Willis, S.G., Foden, W.B., Baker, D.J., Belle, E., Burgess, N.D., Carr, J.A., Doswald, N., Garcia, R.A., Hartley, A., Hof, C., Newbold, T., Rahbek, C., Smith, R.J., Visconti, P., Young, B.E. & Butchart, S.H.M. (2015). Integrating climate change vulnerability assessments from species distribution models and trait-based approaches. *Biological Conservation*, **190**, 167–178.

Wilson, K.A., McBride, M.F., Bode, M. & Possingham, H.P. (2006). Prioritizing global conservation efforts. *Nature*, **440**, 337–340.

Wilson, K.A., Underwood, E.C., Morrison, S.A., Klausmeyer, K.R., Murdoch, W.W., Reyers, B., Wardell-Johnson, G., Marquet, P.A., Rundel, P.W., McBride, M.F., Pressey, R.L., Bode, M., Hoekstra, J.M., Andelman, S., Looker, M., Rondinini, C., Kareiva, P., Shaw, M.R. & Possingham, H.P. (2007a). Conserving biodiversity efficiently: What to do, where, and when. *PLoS Biology*, **5**, 1850–1861.

Wilson, R.J., Gutiérrez, D., Gutiérrez, J. & Monserrat, V.J. (2007b). An elevational shift in butterfly species richness and composition accompanying recent climate change. *Global Change Biology*, **13**, 1873–1887.

Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson, J.B.C., Lotze, H.K., Micheli, F., Palumbi, S.R., Sala, E., Selkoe, K.A., Stachowicz, J.J. & Watson, R. (2006). Impacts of Biodiversity Loss on Ocean Ecosystem Services. *Science*, **314**, 787–790.

Young, B.E., Hall, K.R., Byers, E., Gravuer, K., Hammerson, G.A., Redder, A. & Szabo, K. (2012). Rapid assessment of plant and animal vulnerability to climate change. In: *Wildl. Conserv. a Chang. Clim.* (eds. Brodie, J.F., Post, E.S. & Doak, D.F.). University of Chicago Press, Chicago, IL, pp. 129–150.