GUIDELINES: ADAPTATION, FRAGMENTATION

ENV.B.2/ETU/2006/0042R

Task 1

SECTION 1.1: SYNERGISTIC EFFECTS OF HABITAT FRAGMENTATION AND CLIMATE CHANGE ON EUROPEAN SPECIES

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SECTION 1.2: TECHNICAL ANNEX: ASSESSING THE REQUIREMENT FOR RANGE CHANGE

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SUMMARY

1. Changes in land use patterns over the last century have caused the European landscape to become dominated by a matrix of semi-natural and heavily modified habitats.
2. The negative effects of this process have been most clearly shown by long term population declines for species associated with agricultural landscapes.
3. Habitat fragmentation is the spatially explicit process of breaking up extensive landscape features into disjunct, isolated, or semi-isolated patches. Five major aspects of habitat fragmentation are identified as having impacts on species: 1) fragment area, 2) edge effects, 3) fragment shape, 4) fragment isolation and 5) matrix structure (Ewers & Didham 2006)
4. The effects these impacts have on species include: population declines, loss of genetic diversity, reduction in abundance, reduced habitat occupation, reduced reproductive output, increased mortality, reduced individual fitness and the disruption of biotic interactions such as pollination and parasitism (Opdam & Wascher 2004).
5. The ability of a species to persist within a fragmented landscape is related to its ability to exist in a series of local patches and to re-colonise these patches over time (Hanski 1998). This ability depends on a suite of morphological, behavioural and ecological traits within individuals which interact with the abiotic conditions encountered within the habitat (Swihart et al 2003). In this review we consider the impacts of species traits in more detail.
6. Species traits can be defined as readily observable and measurable features that may be used to predict responsiveness to external events (Diaz et al 2004).
7. Here we review the effects of the following traits associated with fragmentation: rarity, niche breadth (or habitat specificity), individual area requirement, dispersal ability, reproductive potential and longevity, population size and fluctuation, storage effects, trophic level, migratory status and colonisation ability.
8. There is now a good basis to state that anthropogenic climate change is having a direct and measurable impact on species, which will lead to more species being threatened with extinction.
9. Current predictions indicate that warming in Europe should exceed the global mean and should be most severe in winter in Northern Europe and in summer in the Mediterranean region (Christensen et al 2007).
10. Evidence from the palaeontological record and current studies indicate that as conditions change the response of most species will be to colonise new areas as they become suitable and abandon ones (through local extinctions) where conditions deteriorate, leading to range shifts.
11. The general pattern of observed shifts is for species in warming regions to show movements towards the poles (i.e. more northerly latitudes) or increases in altitude (e.g. up mountains).
12. The ability of species to track these changes depends on the availability of suitable habitats within transition and new ranges, and their ability to reach them (Donald 2005). Therefore the ability to shift relies in part on internal traits of the species (e.g. behavioural, morphological and physiological traits) and landscape structure.

13. Range changes in response to changing climatic conditions, therefore, will meet barriers to movement caused by fragmentation. For a species whose range is moving northwards tracking warming trends, colonisation rate in the northern limit of the range is likely to be correlated positively and extinction rate at the southern limit of the range correlated negatively with spatial habitat cohesion.
14. In this paper we identify a number of profiles of species with different sets of species traits that may be most sensitive to habitat fragmentation, and use this to develop an analysis framework that can be used to identify species that are vulnerable to habitat fragmentation and/or climate change.

1. INTRODUCTION

1.1 Background

Habitat loss and fragmentation represent severe threats to biodiversity (MEA 2005, EEA 2005). There is growing concern that as the impacts of climate change become more severe over time, habitat fragmentation will limit the ability of species to respond by shifting their distributions to follow their preferred climate space. Certain species or populations may be less able than others to track changing ecological conditions across the landscape because of their lower ability to overcome physical barriers posed by habitat fragmentation (Opdam & Wascher 2004). Thus some species may be more vulnerable to the synergistic effects of climate change and fragmentation than others.

Potential conservation responses to climate change encompass both mitigation, i.e. reducing the causes of climate change, and adaptation, i.e. making other changes that help organisms respond to climate change. Although mitigation is the only long-term strategy for combating the negative impacts of climate change on ecosystems and species, adaptation strategies are needed to ensure species survival and ecosystem functioning in the short to medium terms. Currently, the leading approach to adaptation for ecosystems on a broad scale is to improve and maintain ecological connectivity and coherence to allow species to move their ranges in response to changing conditions (Opdam & Wascher 2004, Donald 2005).

In the European Community, the Habitats Directive (92/43/EEC) provides the main provision relating to connectivity and coherence of Natura 2000, the European network of protected areas. Ensuring the connectivity of Natura 2000 sites, and other sites of high conservation importance requires the sympathetic management of wider landscapes and land use systems.. Efforts to enhance connectivity could therefore come from a variety of legislative, policy and market tools (e.g. agri-environment schemes, pollution reduction initiatives, etc).

Understanding which approaches to enhance connectivity will be most effective also requires an understanding of the impacts on individual species of habitat fragmentation and climate change. An understanding of which taxonomic groups are likely to be most severely impacted will also support the development and prioritisation of effective conservation plans in the short term.

This study reviews some of the synergies between habitat fragmentation and climate change on species from different taxa and identifies some characteristics of species that may be most vulnerable to the synergistic effects of climate and fragmentation. We identify some simple characteristics and life history traits that could be used to identify those species most at risk. The way these traits could be used to predict vulnerability is illustrated in a limited pilot study. Using climate envelope models for all European bird species, we identify those species whose current climate space is predicted to move the most under current climate projections, and then assess their ability to fill new climate space based on the selected set of life history traits.

The review forms a part of a broader study (ENV.B.2/ETU/2006/0042R) aiming to provide the European Commission with scientifically robust advice on how to guide the Member States in implementing connectivity and coherence-related provisions of the Habitats and Birds Directives. These recommendations and the results of the study form the main contribution that will be integrated into the final guidance submitted to the European Commission.

This review has been undertaken by the World Conservation Union in collaboration with the Institute for European Environmental Policy. The analysis of European breeding birds has been provided by the Royal Society for the Protection of Birds and the University of Durham in the United Kingdom.

1.2 Specific aims of this report

This report aims to:

- Review the scientific literature on the synergistic impacts on wildlife of habitat fragmentation and climate change
- Identify behavioural, ecological or physiological characteristics that may influence the ability of European species to shift their ranges in response to climate change.
- Suggest methods for identifying species and species groups that are particularly threatened by isolation, to allow targeting of specific measures to reduce isolation.

2. THE IMPACTS OF HABITAT FRAGMENTATION ON SPECIES

2.1 What is habitat fragmentation and what are the main impacts on species?

Habitat loss is the leading cause of global and European species decline (MEA 2005, EEA 2005). Habitat fragmentation, the breaking up of habitat into smaller pieces, whose spatial arrangement exerts different pressures on species, exacerbates the effects of habitat loss (Ewers & Didham 2006). Europe is dominated by a matrix of semi-natural and heavily modified habitats. For centuries, humans have modified the European landscape. Major changes include the removal of broadleaf forests during the middle ages and the mass draining of wetlands for agriculture. In the post war period, the single greatest habitat change, in terms of land use change, has come from the intensification of agriculture across Western Europe both through rapid technological improvements in farming practices and the creation of large homogenous fields treated with chemical inputs (Robinson & Sutherland 2002, EEA 2005). The resulting rapid declines in populations of birds associated with farmland provides possibly the strongest example of the impacts of land use change on biodiversity (Krebs et al 1999, Benton et al 2003). These results have also been replicated for other taxa including invertebrates, mammals and plants (Flowerdew 1997, Sotherton & Self 2000, Benton et al 2002, 2003). Because a high proportion of Europe's land surface is now covered by intensively managed agriculture, much of the remaining biodiversity now exists to a greater or lesser extent in islands of natural habitat surrounded by a matrix that is increasingly hostile to most native species (Krebs et al 1999, Robinson & Sutherland 2002, Donald & Evans 2006, Hendrickx et al 2007).

Studies of the impacts of habitat fragmentation on species and the effects of isolation were initially derived from the island biogeography work of MacArthur and Wilson (1967) and later the development of metapopulation theory and landscape ecology (Watling & Donnelly 2006). The relationship between species occupancy, island size and distance from a mainland, namely that the smaller the island and the more distant it was from the mainland the fewer species it contained, demonstrated for oceanic islands by MacArthur and Wilson was taken as an analogue of increasingly isolated habitat patches in mainland situations and later provided the theoretical basis for the development of connective structures such as habitat corridors (Donald 2005). The overall concept that smaller patches further from a 'mainland' are less species-rich holds when comparing real islands to mainland "islands" created by fragmentation, but the relationship has proven more problematic when looking for specific impacts (Gilbert 1980), in part due to differences in the role of the surrounding landscape matrix in restricting the movement of species. The inclusion of landscape ecology principles has removed many of these problems (Ewers & Didham 2006).

The impacts of fragmentation are greatest when patterns of habitat loss cause the remaining habitat to occur in small and isolated patches, rather than in larger blocks of comparable area. Separating the effects of habitat loss and fragmentation is not easy, but fragmentation effects result in a loss of individuals that increases more rapidly than the loss of habitat. In other words, a loss of 50% of habitat is likely to lead to a loss of more than 50% of the individuals present in that habitat, the actual loss being related to the spatial arrangement of the habitat remaining. Through this process there is a net loss of habitat, a higher edge to interior ratio, which introduces new ecological conditions, and increasing isolation of remaining habitat patches. Effective isolation between patches is a function of both the distance between habitat patches and the permeability of the landscape matrix to the movement of species. Theoretical studies have predicted that fragmentation will exert a strong effect when only small areas of habitat remain, typically 20-30% of original cover, although there is little empirical evidence for this specific impact of habitat fragmentation when habitat loss is controlled for (Fahrig 2003). The environmental conditions found within this broader landscape matrix further determine the degree of impact on the remaining habitat patches (Ewers & Didham 2006). As fragmentation is a spatially explicit process, the impacts need to be considered at a spatial scale relevant to the species and habitats of concern. This means that resulting connectivity measures used as responses to fragmentation also need to be viewed at spatial scales relevant to the species in question.

Studies of habitat fragmentation tend to focus on the effects of patch area and isolation on species richness and population processes within and across patches. Most attention has focussed on patch area, which has been shown to be a generally better predictor of species richness than isolation (Watling & Donnelly 2006), although there remains a need for more research on the impacts of isolation and the use of conservation measures such as corridors to mitigate these impacts. Watling & Donnelly (2006) were unable to identify consistent broad taxonomic differences in the effects of habitat patchiness, indicating that either these effects are species and/or site specific, so that research would have to be carried out on a case by case basis, or that conservation actions to improve connectivity may have broad impacts across taxonomic groups.

Habitat fragmentation has been shown to have a number of impacts on species, including: populations declines, loss of genetic diversity, reduction in abundance, reduced habitat occupation, reduced reproductive output, increased mortality, reduced individual fitness and the disruption of biotic interactions such as pollination and parasitism (Opdam & Wascher 2004). As populations become smaller and more isolated, they become more prone to the loss of genetic variation through factors such as random genetic drift, increased self fertilisation in plants, and increased inbreeding in animals (Honnay & Jacquemyn 2007). Although most studies have focussed on the deleterious genetic effects on small populations or rare species, common species can be equally susceptible to the population genetic consequences of habitat fragmentation (Honnay & Jacquemyn 2007).

2.2 Species' responses to habitat fragmentation

The ability of a species to persist within a fragmented landscape is related to its ability to exist in a series of local patches and to re-colonise these patches over time (Hanski 1998). This ability depends on a suite of morphological, behavioural and ecological traits within individuals which interact with the abiotic conditions encountered within the habitat (Swihart et al 2003).Variation in these traits means that the ability to persist will vary both between species and between populations within species (Henle et al 2004b, Ewers & Didham 2005).

Five major aspects of habitat fragmentation are identified as having impacts on species: 1) fragment area, 2) edge effects, 3) fragment shape, 4) fragment isolation and 5) matrix structure (Fig. 1; Fahrig 2003, Ewers & Didham 2006). Separating the impacts of habitat loss and fragmentation on species can be complex as fragmentation necessarily contains elements of loss. Habitat loss has well documented effects including reductions in trophic chain length, changes to species interactions, reductions in the number of specialists, reductions in breeding success and dispersal success and increases in predation rates, which are also impacts of fragmentation (see review in Fahrig 2003). However identifying the impacts of fragmentation per se is more difficult. A review of fragmentation studies identified impacts on species abundance, population persistence, reproduction, species presence/absence, movement and disease incidence (Farhig 2003).

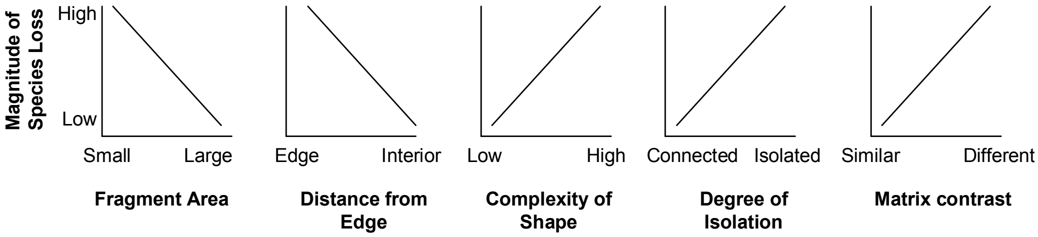


Figure 1: Community responses to habitat fragmentation (from Ewers & Didham 2006)

2.2.1 Patch Area

Habitat loss leads to a reduction in patch size, increasing fragmentation effects. The size and arrangement of individual habitat patches does not change linearly with increasing habitat loss, which means that rapid changes will occur at certain threshold levels of loss (Andren 1994). For species occurring in metapopulations, it is unlikely that they occupy all patches at all times, therefore sufficient connectivity is required to ensure that the rates of colonisation can be maintained. Above a certain threshold level of loss, these colonisation events will become too infrequent, leading to rapid population declines and eventual extinction (Ewers & Didham 2006). This threshold is theoretically postulated to exist at around 20-30% of remaining habitat (Fahrig 2003), but this value varies across species and landscapes. As fragments become increasingly small, populations become increasingly vulnerable to local extinction through stochastic events (demographic or environmental). Population persistence also becomes contingent on the spatial configuration of remaining habitat within the metapopulation structure (Ovaskainen & Hanski, 2004).

2.2.2 Edge Effects

Generally, species richness decreases and community structure changes towards habitat fragment edges. Largely this is based on the responses of individual species to differing conditions (e.g. different micro-climate conditions, species composition and the incursion of species from the surrounding matrix), and species' responses are shaped by life history strategies and habitat requirements (Ewers & Didham 2006). Because edge habitat elicits different responses from species, there are also different patterns of species interaction, such as predation, parasitism or mutualism. Edges seem to also increase the variability of species interactions; however these differences can be mediated by the structure of the surrounding landscape, where complex landscapes can reduce the negative impacts of the edges (Ewers & Didham 2006).

2.2.3 Fragment Shape

Fragments with a more complex shape will have increased edge habitat, and may also become more susceptible to further division of core habitat as peripheral areas become cut off from the remaining habitat patch (Ewers & Didham 2006). At the same time, more complex habitat shapes show consistently higher rates of colonisation and emigration (Ewers & Didham 2006). The impacts of shape on a habitat patch is likely to be related to the patch's size, with small patches being more heavily impacted (Ewers & Didham 2006).

2.2.4 Isolation

As habitat becomes increasingly fragmented, remaining patches become more isolated, forcing individuals to cross more matrix habitat to find other suitable patches. The impacts of isolation are mediated both by distance between patches but also by the structure of the matrix habitat. Isolation can be further exacerbated by 'hostile' features such as highways or cleared areas within forests, which can limit movement even across small gaps (Laurance et al 2002). Increasing isolation leads to reduced recolonisation rates, in turn reducing the likelihood of a patch being occupied.

2.2.5 Matrix effects

The composition of the areas surrounding suitable habitat patches can have an important impact on populations within those patches, and there may be substantial overlap between the species found in patches and in matrix (Ricketts 2001, Vandameer et al 2001). This is something that was not considered within classic Island-Biogeographic approaches to fragmentation, which assumed the marine matrix to be entirely hostile to any species attempting to cross it (Ewers & Didham 2006). In mainland situations, matrix habitat can provide some of the resources necessary for persistence in patches.

Whereas the ecological homogenisation caused by large-scale land modification, e.g. agriculture, can have rapid and strongly deleterious effects on biodiversity within remaining patches, improvements in the diversity of matrix habitat can also help to restore species richness by promoting movement between patches (Donald & Evans 2006, Ewers & Didham 2006). For example, pond breeding amphibians exist in metapopulations that go through local extinctions and regular recolonisation. They also have complex life cycles that require terrestrial and aquatic habitats for feeding and breeding (Rothermel 2004). As a result management actions need to consider connectivity needs, for example juvenile pond breeding amphibians need to have dispersal routes from breeding ponds, otherwise restored ponds could act as population sinks (Rothermel 2004).

The structure of matrix habitat will influence the dispersal ability of species and will determine the extent to which species can move between patches. Diversity within matrix habitat is likely to provide more suitable areas for dispersing individuals and therefore aid dispersal. For example forest birds that were artificially translocated to forest patches of different levels of fragmentation, were equally able to use forest corridors and scrub matrix habitats, whereas they would not cross open areas

(Castellón & Seiving 2006). Dispersal behaviour, i.e. the way in which individuals move through the landscape, is likely to change with landscape structure (Goodwin & Fahrig 2002). Changes to this movement ability have resulting impacts on a host of species interactions such as predation, parasitism, competition, and herbivory. Possibly due to the need for increased mobility, fragmentation adversely affects predators more than herbivores (Zabel & Tscharntke 1998, Tscharntke et al 2002). Also, specialists such as parasitoids are less able to persist in a fragmented habitat than generalists which are better able to exploit the surrounding habitat matrix (Steffan-Dewenter & Tscharntke 2000).

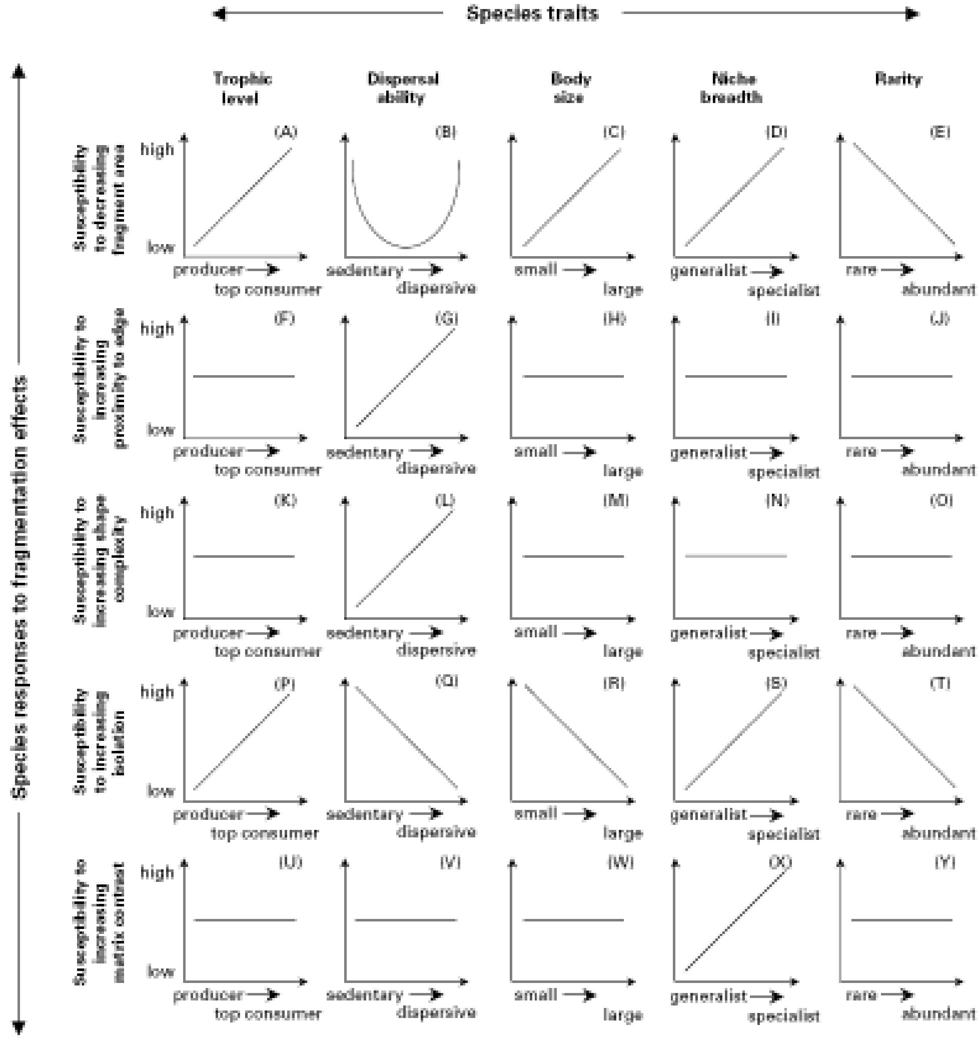


Figure 2: Summary of trait mediated species responses to habitat fragmentation (reproduced from Ewers & Didham 2006).

2.3 Species traits associated with sensitivity to habitat fragmentation

There are a number of factors that may either exacerbate or limit the effects of habitat fragmentation on species, including species traits, climate change, disease spread and time lags in the expression of impacts (Ewers & Didham 2006). For this review, the mediating effects of species traits are considered in more detail and then the possible synergistic impacts of climate change on fragmentation are considered.

Species traits can be defined as readily observable and measurable features that may be used to predict responsiveness to external events (Diaz et al 2004). Several studies have reviewed traits or characteristics displayed by species that may make them more sensitive to the negative effects of habitat fragmentation (Davies et al 2001, Henle et al 2004b, Swihart et al 2003, 2006, Donald 2005, Donald & Evans 2006). Consideration of species traits can help explain observed responses of species to fragmentation and can assist in predicting likely responses of other species. In a review of 12 traits associated in the literature with habitat fragmentation, Henle et al (2004b) identified the following as being particularly important in increasing species' susceptibility to fragmentation: rarity (low natural abundance), high individual area requirement, high population fluctuation, low reproductive potential, low storage effects, intermediate or low dispersal power and specialist habitat requirements.

There is a strong interaction between different traits, with high levels of correlation and co-dependence between them. For example, Davies et al (2004) showed that specialisation and rarity acted synergistically to make beetle species more vulnerable to extinction in forest fragments. Thus a number of traits need to be recognised if they are to be used to make predictions of species' vulnerability. Environmental conditions will also affect the degree to which these traits have an impact, with some only being expressed under certain conditions. In the following sections a series of the key traits associated with fragmentation are considered in more detail (many of these traits are strongly inter-correlated):

1) **Rarity** affects species that naturally occur at low densities, have been historically depleted, or have suffered recent population declines (Henle et al 2004b, Honnay & Jacqemyn 2007). Here we refer to species that have naturally low abundances. Low abundance exacerbates a species' sensitivity to the removal of links between individuals or populations and the subsequent exposure of remaining populations to extinction through demographic and environmental stocasticity.

2) **Niche breadth and habitat specificity** relate to the range of different resources utilised by a species (Swihart et al 2003, 2006). Generalist species can exploit a wide range of resources and have a broad niche; whereas specialists are more limited in the resources they exploit and are less able to switch if these resources become depleted or fragmented. Generalists, however are able to exploit fragmented and successional habitats better than specialists, and are less likely to be impacted by the loss of particular food items due to fragmentation (Swihart et al 2003, 2006).

3) **Individual area requirement or home range size** is the area individuals within a population require for foraging and reproduction. Species with large area needs, i.e. species with large home ranges, which are primarily those at high trophic levels, are more vulnerable to fragmentation (Woodroffe & Ginsberg 1998, Henle et al 2004b).

4) **Dispersal ability** describes the ability of individuals to move through the landscape between patches. As a sensitivity factor this is scale-dependent and

therefore for a species' dispersal ability will help it adapt to fragmentation when it extends beyond the range of environmental fluctuations affecting a patch (Henle et al 2004b, 2004c, Donald 2005). Furthermore, dispersal can occur at different scales for the same species, e.g. plants can undergo regular short distance dispersal and rare long distance dispersal events. Dispersal ability is highly variable between and within taxonomic groups and there may be behavioural adaptations that limit the dispersal ability of species into seemingly suitable habitat; for example, some forest bird species are unwilling to break forest cover when moving between forest patches (Komdeur et al 2004). Dispersal ability, as a sensitivity factor, can also be confounded by the means of dispersal, rate of dispersal and colonisation ability shown by the species (Henle et al 2004b), for example plants that rely on animal dispersal are more vulnerable to the negative impacts of fragmentation than those relying on wind dispersal. Thomas (2000) showed that butterfly species with either low or high dispersal abilities were better able to persist in fragmented habitats, whereas those with an intermediate ability fared worse. It was postulated that low ability dispersers tended to stay within the fragment and high ability dispersers were able to find new habitat patches, whereas intermediate dispersers left their fragments but were less able to find new habitat patches and therefore showed higher mortality (Thomas 2000).

5) **Reproductive potential and longevity** have important effect on sensitivity to habitat fragmentation by determining the number of individuals able to colonise new areas and by buffering against fluctuations in population size (Henle et al 2004b). Longevity and reproductive output are closely correlated. Species with high mortality usually have a high reproductive output and are therefore expected to be able to cope better with changes caused by fragmentation, whereas species with long life-spans generally have a low reproductive output and have been shown to be sensitive to fragmentation.

6) **Population size and fluctuation** are clear indicators of extinction proneness. Species with small population sizes are much more vulnerable to the isolating impacts of fragmentation (Henle et al 2004b).

7) **Storage effects** are primarily associated with plant species and refer to the ability to store reproductive potential across time and generations, for example in seed banks or through clonal propagation (Henle et al 2004b). Examples for animals include species that can remain dormant through periods of unfavourable conditions. Species with high storage effects should be able to delay the negative impacts of fragmentation (Henle et al 2004b).

8) **Trophic level** describes the position of a species within the food web. Species at higher trophic levels (e.g. secondary or tertiary consumers) are expected to have a higher extinction risk from habitat fragmentation generally because they need either larger areas of habitat or are sensitive to disruptions to the trophic levels below them (Ewers & Didham 2006, Valladares et al 2006). Zabel & Tscharntke (1998) showed reductions in predator abundance with increasing fragment isolation in insect communities. However the degree of impact of trophic level may be tempered by the complexity of the food web involved (Henle et al 2004b).

9) **Migratory Status** describes the degree to which species make seasonal movements. Migratory species may be more prone to the effects of habitat fragmentation. Although migrants necessarily need high dispersal ability, they also need a series of different habitat conditions in different locations (e.g. resting sites, breeding sites and feeding sites). However evidence is conflicting, with some studies showing that residents are more sensitive to fragmentation than migrants (Mönkkönen 1992, Imbeau et al 2001) and others showing no effect (Pavlacky & Anderson 2007).

   An important distinction can be made between broad front migrants that travel short distances at a time and stop frequently, and leap migrants that stop infrequently, often in large numbers, and travel long distances in each journey (Robinson et al 2005). Migration is an adaptive strategy to meet ecological conditions and to a certain extent is flexible to changing environmental conditions. Changes in the timing of migration have important implications for life history events such as breeding, and there is evidence of the impacts of the mismatches in the timing of migration (e.g. Both et al 2004).

10) **Colonisation ability** refers to the ability of a species to colonise new areas once they immigrate. Generally species that are short lived and have a high reproductive output have a high colonisation ability and are pioneers within a new area. Such individuals tend to have a small body size, short generation time and high fecundity. Species that take longer to establish within an area and generally have a lower colonisation ability tend to produce fewer offspring ensuring that there a higher survival, with longer generation times and life spans. A useful proxy for this measure is age at first breeding.

3. THE INTERACTION OF CLIMATE CHANGE AND HABITAT FRAGMENTATION AS A DEVELOPING THREAT

3.1 The predicted impacts of climate change in Europe

The latest assessment from the International Panel on Climate Change (IPCC) indicates that warming in Europe should exceed the global mean and should be most severe in winter in Northern Europe and in summer in the Mediterranean region (Christensen et al 2007). Central and Southern Europe are predicted to face reductions in precipitation, whereas Northern Europe may see more, and more extreme, precipitation events. As a result, the moisture retained by soils in the Mediterranean and Central Europe is predicted to decline. In Northern Europe the predictions remain unclear as the possible reductions in moisture because warming may be counter-balanced by earlier snow melt and increased precipitation (Christensen et al 2007). Throughout Europe, the snow season is expected to become shorter and snow depth will decrease. These changes could be most extreme in Northern Europe. However the coldest parts of Europe, the Alpine peaks, Northern Scandinavian and Russia, seem less sensitive to the projected changes this century and therefore may act as refuges for cold tolerant species. Sea ice in the Arctic and Baltic Seas is expected to contract significantly throughout the century.

As a result Europe is expected to experience more extreme weather events such as heat waves, and with increasing frequency. Due to predicted changes in precipitation, Northern Europe is expected to experience more extreme precipitation events in winter, whereas the Mediterranean may experience a greater risk of drought in summer.

The impacts of these predicted changes on European ecosystems and habitats are likely to be complex, for example increased winter precipitation could favour certain habitats such as wet heath, but this effect could be counter-balanced by more summer droughts (Hopkins et al 2007). The Arctic is witnessing reductions in perennial sea ice which is thinning and being replaced by seasonal ice (Nghiem et al 2006). Tundra habitats are expected to become highly fragmented and reduced due to climate change. There is little area for the habitat to move to as climates change, being limited by the Arctic Ocean. On its Southern border, tundra is expected to be replaced by coniferous boreal forest and shrubland (Zöckler & Lysenko 2000). This reduction in tundra and permafrost is also expected to reduce the reflectance of solar radiation (Callaghan et al 2005), and may increase the incidence of wildfires (Raccine et al 2004). As tundra provides the breeding habitats for geese and other avian migratory species, major declines can be expected. Further south boreal forest, which provides the worlds largest stores of organic carbon, are expected to move 150–550 km northwards over the next century (IPCC 2001b). Warming may also release carbon stored in the permafrosts of Siberia and also make conditions more tolerable to pest species, which may spread rapidly.

At the extreme of the altitudinal gradient, Europe's mountains have been identified as of particular threat from climate change. As Mediterranean conditions start to move north the Alps will experience warmer and wetter winters and dryer summers (IPCC

2001a). The snow pack on European mountains is close to its melting point and so is particularly sensitive to temperature changes. For every 1°C increase in temperature, the snowline rises by about 150 m, thus less snow will accumulate at lower elevations (IPCC 2001) Furthermore, changes to the timing and amount of run-off into Europe's major river systems will be affected leading to water shortages in some areas and increased frequency of floods in others. Europe's glaciers are also predicted to continue to recede and it is likely that 30–50% of alpine glaciers will disappear this century (Haeberli, 1995 in IPCC 2001).

As a result of these observed and projected impacts, climate change is likely to place increased pressure on coastal and aquatic ecosystems, Mediterranean habitats, montane areas and arctic regions. Additionally for a certain period at least growing conditions in Central Europe will likely increase, which may present additional pressures from increases in agricultural or forestry practices.

3.2 General species responses to climate change

Based on the rapidly expanding literature describing past and current species responses to changing climate conditions, there is now a good basis to state that anthropogenic climate change is having a direct and measurable impact on species (see reviews in Parmesan & Yohe 2003, Root et al 2003, Root & Hughes 2005, Parmesan 2005, 2006). This impact is expected to increase the number of species threatened with extinction (Thomas et al 2004).

Species show a range of tolerances to environmental conditions and responses to changes in those conditions. Climate has a number of direct and indirect impacts on species. The extent and effects of direct physiological impacts such as increased UVB radiation in amphibians are less well-known than the more indirect impacts that affect habitat conditions and ecosystem dynamics that define the ecological conditions for species. Generally responses can be separated into two broad categories: range changes and phenological changes. In a meta-analysis of 99 bird, butterfly and alpine shrub species ranges and 172 species for phenological events, Parmesan & Yohe (2003) show that on average species range limits has moved 6.1 km (± 2.4 km) per decade towards the poles and that spring timings are 2.3 days earlier per decade. In this review we consider the potential for climate change to exacerbate the effects of habitat fragmentation on species, and their ability to respond to these changes. Therefore we focus the following discussion on range change in species as a response to climate change, whilst recognising that this is one of many direct impacts that climate change is having.

Range Change

Evidence from the palaeontological record and current studies indicate that as conditions change the response of most species will be to colonise new areas as they become suitable and abandon ones (through local extinctions) where conditions deteriorate, leading to range shifts. The ability of species to track these changes depends on the availability of suitable habitats within transition and new ranges, and their ability to reach them (Donald 2005). Therefore the ability to shift relies in part on internal traits of the species (e.g. behavioural, morphological and physiological traits) and landscape structure. The potentially synergistic effects of landscape structure and climate change are therefore though poorly understood (Honnay et al 2002, Opdam and Wascher 2004). The degree of habitat fragmentation and the spatial structure of the landscape surrounding suitable patches (e.g. the habitat matrix) could place signification barriers in the way of species responding to climate change. Of course species range change will be both positive and negative in the sense that warming will create more favourable conditions for some species. In a review of 32 species of mammal, bird, plant and invertebrate in the UK, the MONARCH project projected that climate space would increase for 15 species, decrease for 8, no significant change for 3, relatively neutral change in space for 6 species (Walmsley et al 2007).

The general pattern of observed shifts is for species in warming regions to show movements towards the poles (i.e. more northerly latitudes) or increases in altitude (e.g. up mountains). Most studies observing range shifts concentrate on range boundaries or species composition within species geographic areas, whereas few studies assess whole species range changes. Parmesan et al (1999) assessed the entire ranges of 57 butterfly species in Northern Europe and found that 63 per cent showed a northward extension of their range boundaries, while Southern boundaries tended to remain stable. For European tree species, climate envelope models predict that boreal deciduous and coniferous species will experience range reductions, being replaced by temperate deciduous and coniferous species, which will increase the functional species diversity of boreal areas (Thuiller et al 2006). This move is also matched by a predicted northern expansion of Mediterranean evergreen and deciduous species, which are currently limited by winter temperature and growing season length (Thuiller et al 2006).

3.3 Interactions between climate change and habitat fragmentation

As has been stated, Europe has a highly fragmented landscape, which contains pockets of natural habitat embedded within large areas of man-made habitats. Range changes in response to changing climatic conditions, therefore, will meet barriers to movement caused by fragmentation. For a species whose range is moving northwards tracking warming trends, colonisation rate in the northern limit of the range is likely to be correlated positively and extinction rate at the southern limit of the range correlated negatively with spatial habitat cohesion. The degree of impact of climate change and fragmentation will also be mediated by species traits and also positive feedback loops where higher temperatures may improve certain habitat conditions for some species. Furthermore warming is likely to improve, at least in the short term, growing conditions for agriculture and therefore will have impacts of the conversion of land to agriculture or intensification of existing agricultural areas (Opdam & Wascher 2004). This is likely to increase the degree of fragmentation in many European managed landscapes.

3.4 Taxonomic group responses to fragmentation and climate change

The following section provides a summary of the existing literature concerning the likely impacts of the synergy between habitat fragmentation and climate change on taxonomic groups in Europe.

3.4.1 Plants

Identifying possible future range shifts in plant species is difficult. The paleo-record shows that plants responded to climate change in the Quaternary period by large-scale range changes (Thuiller et al 2006) and responses could be rapid, i.e. within decades of the impact (Peteet 2000). However studies of European tree species suggest that trees and tall shrubs have yet to realise the climate space that is available to them since the last glacial period and that their dispersal is limited by other factors (Svenning & Skov 2004). Thus their ability to track future climate change at the accelerated rate it is predicted to have could be limited. Mountain plant species that have adapted to specific environmental conditions and have narrow niche tolerance are predicted to show the highest rates of species loss in Europe (Thuiller et al 2005b), whereas Mediterranean and Pannonian plain species may remain well-adapted to changing conditions.

It is often assumed that the ability of plants to track climate change and to disperse within a fragmented landscape will be limited and will be outpaced by changing climates. However, this may depend largely on the methods of dispersal used. Migration in plants will either occur by a short distance slow expansion along one front of their range limit, or by rarer and more rapid long distance dispersal events. Long distance dispersal requires two steps: the movement and then the successful colonisation at the other end. Nielsen et al (2005) identify four basic elements that need to be considered when looking at migration ability: reproductive outputs, dispersal, establishment and growth to reproductive maturity. Long distance dispersal is most often achieved by either wind or animal vectors.

Chust et al (2006) compared the spatial patterns of plant species in fragmented Mediterranean scrubland and grassland. They showed that for scrub, the establishment of communities depended more on the proximity of source populations than for grasslands and that communities developed over longer time periods of slow expansion. Grasses by contrast have more short-lived, wind dispersed species that can colonise open areas rapidly. This would indicate that in the absence of other pressures grasslands may be better able to cross fragmented landscapes than other plant communities such as scrub. Certain plant types, such as annual herbs, should be better able to respond to climate change as they are rapid dispersers (Lavorel et al 1997). However it has been shown that landscape structure (e.g. the degree of fragmentation) interacts with reproductive strategy, making predictions difficult (Chust et al 2006).

Increasing connectivity provides an important tool to support the maintenance and recovery of forest areas and the understory species associated with them (Verheyen et al 2006). For example, Petit et al (2004) showed that for ancient woodland in the UK, structural connectivity elements such as hedgerows and tree-lines were important for improving species diversity in forest patches. It is clear however that the specific connectivity measures used to support plant communities will differ based on the migration ability, reproductive outputs, dispersal, establishment and growth patterns of the species concerned.

3.4.2 Invertebrates

Insects make up the majority of European animal species. The four major insect groups - Coleoptera, Diptera, Lepidoptera and Hymenoptera - represent the major functional groups of herbivores, pollinators, parasitoids and predators (Steffan-Dewenter & Tscharntke 2002). Butterflies are highly visible and charismatic group and are therefore relatively well-known and many of the first studies of the impacts of climate change on wildlife were conducted on European and North American butterfly species (e.g. Parmesan et al 1999, Hill et al 1999, Thomas et al 1999). In one of the first continental scale studies, Parmesan et al (1999) showed poleward range shifts for 35 species of European butterfly. As with other taxonomic groups, butterflies respond idiosyncratically to climate change. The Speckled Wood butterfly (*Pararge aegeria*), which is a generalist without specific habitat requirements, has expanded its range in response to temperature changes, and predictions indicate that it should expand to more northerly regions beyond the middle of Scandinavia (Hill et al 1999). In the UK habitat specialist and sedentary butterfly species have been declining for the past 30 years, primarily due to land use changes, whereas generalist species have been able to extend their ranges northwards (Thomas 2005).

Fragmented habitats are associated with lower insect richness, and isolation seems to affect predatory species more than herbivores (Zabel & Tscharntke 1998, Tscharntke et al 2002). Specialists such as parasitoids suffer more than generalists, which are able to exploit the surrounding habitat matrix (Steffan-Dewenter & Tscharntke 2000). Landscape structure and the nature of the surrounding habitat matrix will have important effects on the species within habitat patches Predicting the connectivity needs of invertebrates will be complex and highly species specific. Often these species are reliant on micro-habitat conditions which will be altered dramatically by climate and habitat fragmentation. However, landscape management that both increases or maintains habitat heterogeneity and softens the matrix surrounding habitat patches should help insects cross fragmented landscapes. In practical terms this will include measures such as agri-environmental schemes that, among others actions, can maintain verges, restore hedgerows, ditches and ponds (Donald & Evans 2006).

3.4.3 Amphibians and Reptiles

Herpetofauna, being ectothermic and reliant on ambient temperature and solar radiation to regulate their body temperatures, require specific climate conditions (Blaustein et al 2001, Araújo et al 2006). Amphibians also require moist conditions and water for the reproductive stages of their life cycles. Habitats and the routes they may use to move between patches need to maintain the necessary moist conditions they require (Root & Schneider 2002). This makes these species highly susceptible to habitat fragmentation and degradation. In general, amphibians can tolerate higher temperatures better than low and therefore the main threats from climate change are thought to be from a reduction in precipitation rather than increasing temperature (Araújo et al 2006).

The European diversity of herpetofauna is thought to reflect glacial history, with largely ice free areas around the Mediterranean basin being the most species rich. Araújo et al (2006), used climate models to test the hypothesis that climate change is causing amphibian and reptile declines in Europe. They used climate envelope models of 42 amphibian and 66 reptile European species and found a longitudinal pattern to the projected changes in species range under climate change, with contracting ranges to be found in the Iberian Peninsula, Southern France and Northern Scandinavia. In general if dispersal was unlimited ranges were expected to increase and northern areas became more hospitable, but under limited dispersal range declines occurred. These declines were most strongly identified for South Eastern European, which contains the highest species richness for herpetofauna primarily due to the drying of suitable habitat. A smaller impact has been predicted for South Western Europe. Due to their limited dispersal ability, both amphibian and reptile species are identified as of particular concern from habitat fragmentation and climate change (Williams et al 2000 in Araújo & Pearson 2005). However, one study found positive fitness consequences for mountain populations of the Common lizard *Lacerta vivipara*, in which females showed increases in body size and fecundity over an 18 year period, closely correlated with increases in temperature (Chamaille-Jammes et al 2006).

For both amphibians and reptiles, the maintenance of local population dynamics and connectivity between populations are essential for long term survival (Semlitsch 2002). Pond breeding amphibians exist in metapopulations, exhibiting local extinctions and regular recolonisation. They also have complex life cycles that require terrestrial and aquatic habitats for feeding and breeding (Rothermel 2004). Reptiles and amphibians are generally identified as intermediate dispersers (Donald 2005), and this could make them more susceptible to fragmentation than if they were either sedentary or highly dispersive (Ewers & Didham 2006), and therefore in need to specific connectivity measures.

Management actions also need to take account of the dispersal needs of the juveniles after they are hatched, otherwise restored ponds could act as population sinks (Rothermel 2004). Therefore conservation measures need to take place at both the site level (e.g. restoration of ponds) and the landscape level (e.g. migration routes, buffer zones etc) (Semlitsch 2002, Rothermel 2004). At a European level one of the major impacts on amphibians has been the degradation or draining of ponds and wetlands used for breeding, which are often associated with high quality agricultural land. Examples of such species include the fire-bellied toad (*Bombina bombina*) and great-crested newt (*Triturus cristatus*). Both amphibians and reptiles have been the targets of numerous habitat protection and restoration projects under the EU LIFE programme, and actions taken include communication with farmers, protection and restoration of ponds, the creation of new ponds and the captive breeding and release of species.

3.4.4 Birds

Birds are the best studied group in terms of understanding impacts of climate change. Their high visibility and the long history of data collection on range sizes and phenological events (eg. nesting, migration etc) means that there are extensive data sets concerning changes over the past century. Birds are also often considered to be capable of crossing fragmented landscapes due to their high dispersal ability, although many species show behavioural inhibitions to crossing unsuitable habitat to move between patches (Donald 2005).

Several authors have suggested that the most important impact of fragmentation on birds is reduction in patch size rather than patch isolation, as they were unable to show an effect on species loss of isolation (Haila et al 1982, Tilghman 1987, Hart & Horowitz 1991, Opdam et al 1995 Bellamy et al 1996). Hannon & Schmiegelow (2002) and Schmiegelow & Mönkkönen (2002) demonstrated few, if any, benefits of corridors in reducing the effects of fragmentation on boreal forest birds, suggesting instead that loss of habitat area was more important than loss of connectivity. The northern European avifauna largely comprises species that have had to respond to changes in their distributions many times in the past, and over huge areas, following the advance and retreat of successive Ice Ages, and so may be capable of changing distributions. Most UK bird species should be able to disperse to suitable new areas if they exist (Harrison et al 2001). This suggests that for most avian species the most effective tools to improve connectivity are to improve the permeability of the landscape to dispersal and increase the size of habitat patches.

3.4.5 Mammals

The evidence for current range shifts in mammals is more scarce than for other taxonomic groups, with most of the evidence coming from North America. However knowledge from the paleontological record and the last inter-glacial warming periods shows that species ranges in the Northern Hemisphere have undergone dramatic changes in response to past climate change, with those at higher latitudes being more strongly impacted than those at lower latitudes (Guralnik 2006). Barnosky et al (2003) compared mammalian community changes in the Rocky Mountains over the last four major warming periods. They showed that phenotypic and density changes were noticeable within 100 years of warming, and as warming extends over 1000 years, large reduction in mammals richness are observed (Barnosky et al 2003).

Desert big horn sheep (*Ovis Canadensis nelsoni*) from the arid mountains of Southern California in the USA, occur in naturally fragmented populations characterised as metapopulations (Epps et al 2004). Populations have a high turnover, and Epps et al (2004), showed that population extinction over time was non-random and closely correlated to elevation, annual precipitation and presence of water holes. Epps et al (2004) suggest that the correlation between low elevation and increased population extinction risk, is associated with ambient temperature increases reducing the plant growing season at lower elevations. More research is certainly needed to study the impacts of fragmentation and climate change on mammals, especially as they represent a group with a high variation in life history traits.

4. A METHODOLOGY FOR IDENTIFYING SPECIES LIKELY TO BE LESS ABLE TO TRACK MOVING CLIMATE ENVELOPES

4.1 Identifying traits using European Birds species

In the previous sections we identified a number of traits that may make species more vulnerable to habitat fragmentation and so less able to track moving climate envelopes. Previous authors have shown that these traits are highly species specific, and finding broad agreement across taxonomic groups is difficult, most likely because of interactions between different traits and environmental conditions (Henle et al 2004b).

In this section we identify a sub-set of these traits and compare them against data generated from climate envelope models for European breeding birds. The results presented here are a summary of the full analysis that is presented in the Technical Annex. Existing climate envelope models for all European birds were used to project the future available climate space for each species based on different climate scenarios. We compare the overlap between current and predicted future climate space to identify the 50 most vulnerable species, i.e. those whose climate space is projected to move the most. Then existing data sources were used to classify each species according to a number of predefined traits. Then, based on the literature review and this pilot test, we propose a practical methodology to use species traits to identify species for which habitat fragmentation is likely to pose a particular hindrance to tracking future shifts in climate envelopes.

4.1.1 Results of climate predictions

The majority of European birds had predicted future ranges that were smaller than their current range. For three European species there was no overlap between current and future range; Dupont's lark, Berthelot's pipit and Trumpeter finch. Using the methodology established by Berry et al (2006) we calculated an index of vulnerability for each species and identified a strong negative correlation between this measure and existing range size; the larger the current range size, the less the requirement for future shifts to track climate envelopes. Therefore a simple proxy of the need for future range shifts to track moving climate envelopes could be current range size. Significantly more vulnerable species were listed on Annex 1 of the Birds Directive than not.

4.1.2 Results of the species traits assessment

We estimated the following traits from the literature: niche breadth (habitat specificity and food specialism), habitat requirement (seral or climax), reproductive output (age at first breeding), current fragmentation, disturbance tolerance, trophic level, migratory status and population trend (1990-2000).

Table 1 shows the results for the top 50 species whose climate envelopes move the greatest. High risk traits are highlighted in the table. Although most species showed at least two of these traits there was wide variation. Figure 3 shows the frequency distribution of the number of traits identified for each species. The results indicate that some of the species, whose climate space is predicted to change significantly over time, could have difficulty responding to this change. Examples of such species include Dupont's lark (5 traits), Bearded Vulture (5 traits), White-tailed Eagle (5 traits) and Spanish Imperial Eagle (6 traits). Dupont's lark has a restricted and small breeding population in the Spanish Steppe had has undergone habitat loss and fragmentation from agricultural intensification within this range (Tella et al 2005). Similarly the Bearded Vulture and Spanish Imperial Eagle are range restricted Mediterranean species that are declining in at least part of their range (Birdlife International 2004). The white tailed eagle by contrast has undergone population increases in Europe and in the last Red List assessment was down-listed from Near Threatened to Least Concern globally. It still has a patchy distribution with a relatively small breeding population (Birdlife International 2004). This species was identified as potentially vulnerable because its climate space is predicted to decline and it is a top predator found in fragmented habitats.

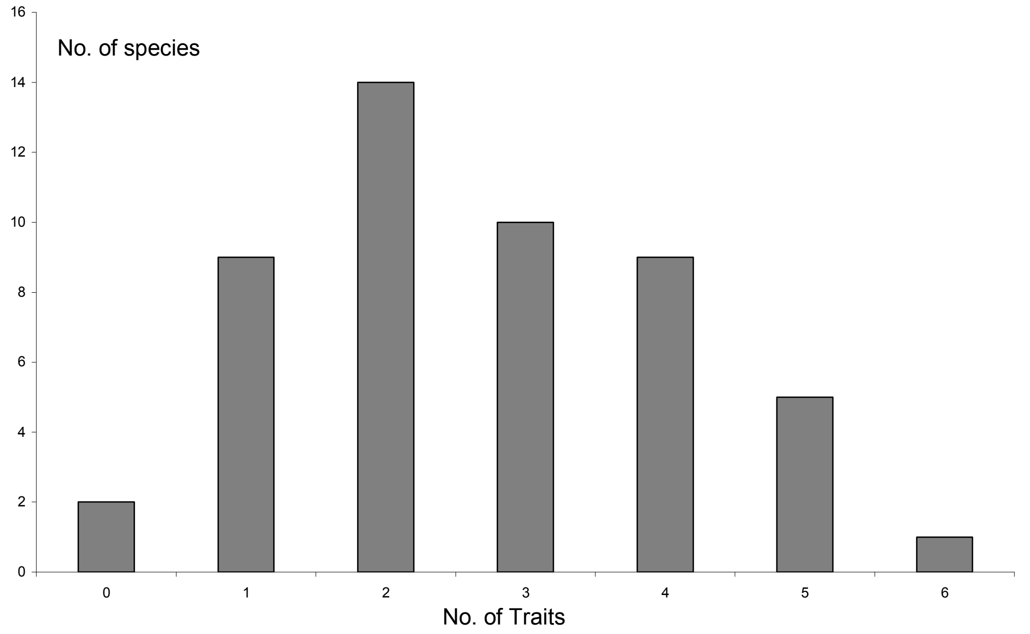


Figure 3. The number of species showing zero or more of the traits associated with vulnerability to climate change and habitat fragmentation.

This pilot study provides some promising results which indicate that traits could be used to identify species of concern from climate change and habitat fragmentation. It is clear that the traits and most importantly the criteria used to score them needs much more detailed consideration and testing with a range of taxonomic groups.

Species Name	Countries	*O*	VB	Habitat specificity	Food specialism	Age first breed	Current fragmentation	Seral/ climax	Disturbance tolerance	Trophic level	Migratory status	Pop. trend, 1990-2000	Count
Chersophilus duponti	1	0.000	20	high	low	1	high	seral/climax	low	low	Resident	-1.4344	5
Rhodopechys githaginea	5	0.000	20	high	low	1	high	climax	high	low	Resident	-0.166	4
Oxyura leucocephala	5	0.000	20	high	low	2	high	climax	med	low	Partial	1.0045	2
Alectoris barbara	3	0.012	20	med	low	1	low	seral/climax	med	low	Resident	-0.1556	2
Phoenicopterus ruber	6	0.000	19	high	high	5	high	climax	low	low	Partial	2.8678	5
Anser erythropus	4	0.268	19	low	med	3	med	climax	low	low	Short-distance	-0.7375	3
Larus audouinii	8	0.052	19	med	med	2	med	climax	med	med	Partial	2.5272	0
Puffinus yelkouan	9	0.033	18	low	high	5	high	climax	high	med	Partial	-0.5303	4
Branta leucopsis	13	0.291	18	low	med	3	med	climax	low	low	Short-distance	3.6193	2
Cygnus columbianus	3	0.281	18	low	low	4	med	climax	low	low	Short-distance	1.2065	2
Porphyrio porphyrio	8	0.149	18	med	low	1	med	climax	med	low	Resident	2.5543	1
Circus macrourus	6	0.051	18	med	low	2	low	climax	med	high	Long-distance	-2.8285	2
Aquila clanga	9	0.123	18	med	low	4	low	climax	low	high	Short-distance	-1.1098	4
Nyctea scandiaca	7	0.299	17	low	med	2	low	climax	med	high	Partial	-0.4081	2
Sylvia sarda	3	0.098	17	med	low	1	high	seral/climax	med	low	Partial	-0.2762	2
Gypaetus barbatus	12	0.051	17	med	high	5	high	climax	med	high	Resident	0.8883	5
Limosa lapponica	4	0.184	17	med	low	2	low	climax	med	med	Short-distance	-0.7937	1
Mergellus albellus	6	0.172	17	med	med	2	low	climax	med	med	Short-distance	0.4892	0
Eudromias morinellus	13	0.298	16	high	med	2	med	climax	med	low	Short-distance	-1.073	2
Gallinago media	10	0.331	16	high	low	1	med	seral/climax	low	med	Long-distance	-1.0043	3
Otis tarda	14	0.066	16	low	low	4	high	seral/climax	low	med	Partial	-0.9953	4
Calonectris diomedea	11	0.083	16	low	high	?	high	climax	med	med	Short-distance	-0.6853	3
Galerida theklae	3	0.280	16	low	low	1	med	seral/climax	med	low	Resident	-0.347	2
Falco rusticolus	6	0.342	16	low	high	2	low	climax	med	high	Partial	-0.1048	3
Oenanthe leucura	3	0.221	16	med	low	1	high	seral/climax	med	low	Resident	-4.2821	3
Phalaropus lobatus	10	0.323	16	med	med	1	med	climax	high	low	Long-distance	-1.14	1
Tringa cinerea	5	0.227	16	med	med	1	med	seral/climax	med	med	Long-distance	-0.07371	1
Gyps fulvus	17	0.240	16	med	high	4	high	climax	med	high	Partial	0.7236	4
Strix nebulosa	6	0.264	16	med	high	2	low	climax	med	high	Resident	1.0653	3
Sitta krueperi	4	0.000	15	high	med	1	high	climax	med	med	Resident	-0.4878	4
Loxia scotica	1	0.000	15	high	high	1	high	climax	med	low	Resident	*	4
Acrocephalus paludicola	8	0.004	15	high	low	1	high	seral/climax	med	low	Long-distance	-0.656	3
Recurvirostra avosetta	33	0.126	15	high	med	2	high	climax	med	med	Partial	0.7146	2
Fulica cristata	1	0.222	15	low	low	1	high	climax	med	low	Resident	-5.4344	3
Marmaronetta angustirostris	7	0.194	15	low	low	1	high	climax	med	low	Partial	1.7979	1
Apus caffer	2	0.000	15	low	high	?	high	climax	med	med	Short-distance	4.5401	2
Larus melanocephalus	25	0.028	15	low	med	2	high	seral/climax	med	med	Short-distance	2.6299	1
Falco vespertinus	17	0.249	15	low	high	1	med	seral/climax	med	med	Long-distance	-0.4171	2
Oenanthe pleschanka	8	0.209	15	low	low	1	high	seral/climax	med	low	Long-distance	0.7517	1
Emberiza cineracea	2	0.000	15	med	low	1	high	climax	high	low	Short-distance	0.1995	1
Tetrax tetrax	8	0.215	15	med	med	2	high	seral/climax	low	med	Partial	-0.3498	3
Pyrrhocorax pyrrhocorax	18	0.233	15	med	med	4	high	climax	med	med	Resident	0.07488	3
Sterna caspia	8	0.152	15	med	med	3	high	climax	low	high	Long-distance	0.5545	4
Casmerodius albus	22	0.155	15	med	med	2	high	climax	med	high	Partial	2.4152	2
Platalea leucorodia	26	0.075	14	high	med	3	high	climax	low	med	Short-distance	1.4694	4
Milvus milvus	28	0.211	14	low	med	2	high	seral/climax	med	high	Partial	0.6304	2
Aquila adalberti	2	0.123	14	med	high	4	high	seral/climax	low	high	Resident	2.9401	6
Aquila heliaca	18	0.091	14	med	high	4	high	seral/climax	low	high	Partial	0.4686	5
Phalacrocorax pygmeus	18	0.133	14	med	med	?	high	climax	med	med	Partial	1.2265	1
Haliaeetus albicilla	29	0.253	14	med	high	5	high	climax	low	high	Partial	2.2061	5

Table 1: The Top 50 most vulnerable species (VB), based on the overlap between current and future climate space (*O*). The table shows the countries the species are found in and the traits associated with each species (see text and Annex 1 for details).

4.1.3 Habitat associations of species vulnerable to climate induced range shifts

A wide range of habitats are used by the top 50 species which had the lowest overlap between current and projected future climate space. Nevertheless, there is a suggestion that a disproportionately high number of sensitive species occur in heath, scrub and tundra habitats. In contrast some other widespread habitats such as marine and inland surface waters (i.e. wetlands) appear to be underrepresented.

Comparison of the habitat use and occurrence within biogeographic zones indicates that particularly high proportions of species sensitive to this impact of climate change occur within tundra, mire and forest habitats in the Arctic and boreal realms. This is in accordance with some predictions that such species in northern tundra regions would be particularly sensitive because there is little potential for their climate space to move northwards and remain on land. However, several of the boreal forest species (e.g. Scaly Thrush) have small ranges in Europe that are marginal to their large Asian range. Their apparent high sensitivity may therefore be an artefact linked to their small range size. The results also suggest that a high proportion of climate change sensitive species occur in Mediterranean habitats and are associated within scrub habitats (e.g. maquis and garrigue) and dry grasslands. This result was not expected as it is often assumed that southern species will be able to move north in relation to climate change. However, examination of changes in range ratio indicates that several Mediterranean species will lose all or a large proportion of their climate space. It therefore seems likely that movement of the Mediterranean climate space currently inhabited by species is constrained by some factor other than the sea. This could be the presence of higher ground to the north (such as the Alps, Pyrenees and lower hill ranges) that may constrain climate space movements. But it is not possible to examine this hypothesis any further within the scope of this study.

Thus, overall this analysis shows that there is a clear indication that tundra habitats are likely to hold a high proportion of species that are sensitive to the climate change scenarios adopted in this study. Species in marine and coastal habitats in the Mediterranean and Arctic regions may also be relatively sensitive. There is also a suggestion that species associated with Mediterranean scrubland and grassland habitats will be sensitive to climate changes, but the statistical evidence for this is less clear.

4.2 Developing a methodology to identify species most at risk

The most sensitive species to fragmentation should be those with low dispersal power and high individual area requirements, however, it may be difficult to identify such species in practice (Vos et al 2001, Henle et al 2004b). Based on their review of the impacts of habitat fragmentation on species, Henle et al (2004b) developed the following series of fragmentation vulnerability profiles:

1) **Highly vulnerable species have**: low natural abundance and/or high individual area requirement, high population fluctuations, low reproductive potential, low storage effects, intermediate or low dispersal power, and specialised habitat requirements.

2) **Vulnerable species**: low population size and density, large area requirements, and high mobility. Such species may have difficulties responding to even moderate habitat loss if reproductive output is low. However, these species should cope fairly well if remaining habitat is concentrated in a few more distant but larger remnants.
3) **Less vulnerable species**: low to moderate dispersal but high density and low population fluctuations. Such species should be relatively insensitive to the spatial effects of fragmentation.

These profiles together with the review of traits above has been used to as a basis for a habitat fragmentation and climate change risk assessment framework. It is suggested that this can be used as a tool for initially identifying species of Community interest (which, for the purpose of these guidelines, are considered to be all species currently listed under Annex 2 or 4 of the Habitats directive, Annex 1 of the Birds directive and migratory bird species relevant to Article 4 of the Birds directive) that are vulnerable to habitat fragmentation and/or climate change. Species that are considered to be vulnerable to fragmentation and/or climate change should then be subject to a detailed assessment of their connectivity requirements at an appropriate biogeographic scale in relation to existing and potential habitat fragmentation and /or climate change impacts. The framework has a hierarchical approach to the treatment of information, such that scientific evidence of fragmentation or climate change impacts triggers the requirement for a detailed assessment, irrespective of the number of fragmentation and climate change vulnerability traits that the species exhibits.

The overall risk assessment process is presented in Figure 4 and described in more detail below.

Description of the fragmentation and climate change risk assessment steps

1) **Does the species have an unfavourable conservation status and is fragmentation considered to be a contributory factor?**

   Assessments of conservation status normally indicate the main threats faced by a species and also provide life history or demographic data that can be used to assess the species' vulnerability to fragmentation.

   1.1 **If YES:** Go to Step 4.
   1.2 **If NO:** Go to Step 2.

2) **Have scientific studies indicated that the species is vulnerable to the effects of habitat fragmentation?**

   Species that may be in FCS could be undergoing widespread but shallow declines (or be constrained) due to changes in habitat quality, quantity and fragmentation. Is there existing information in peer-reviewed literature or technical reports to indicate that the species is vulnerable to habitat fragmentation?

   2.1 **If YES**: Go to Step 4.
   2.2 **If NO:** Go to Step 3.

3) Is the species at risk from fragmentation according to an assessment of the following vulnerability traits?

Using existing knowledge concerning the demographic parameters and life history traits of the species compare the species traits against the risk categories in Table 2.

Table 2. Fragmentation risk categories associated with species' traits

TRAIT	RISK CATEGORY		
	LOW	MEDIUM	HIGH
ABUNDANCE	COMMON	MEDIUM	RARE
INDIVIDUAL AREA REQUIREMENT	LOW-MEDIUM	MEDIUM	HIGH
NICHE BREADTH (HABITAT SPECIFICITY)	BROAD (GENERALIST)	NARROW (SPECIALIST)	NARROW (SPECIALIST)
DISPERSAL ABILITY/MOBILITY	HIGH	MODERATE-HIGH	LOW -MODERATE
REPRODUCTIVE POTENTIAL	HIGH	LOW	LOW
POPULATION FLUCTUATION	LOW	HIGH	HIGH

Does the species fall within the moderate or high risk categories (i.e. columns) for three or more traits OR fall within the high risk category regarding individual area requirements and dispersal ability?

1.1 **If YES**: The species is at risk from fragmentation. Go to Step 4.

1.2 **If NO:** the species is unlikely to be at risk from habitat fragmentation. However, the effects of climate change may act to increase vulnerability in the future. Fragmentation may also constrain a species' ability to adapt to climate change by moving to new areas with suitable climates. Therefore go to Step 5.

4) Carry out a detailed assessment of connectivity requirements in relation to existing and potential habitat fragmentation and climate change impacts

The assessment should include consideration of the potential synergistic impacts of climate change and fragmentation on the species, irrespective of the species' vulnerability as assessed under Steps 5 and 6 below. The assessment should be carried out at an appropriate biogeographical scale (through collaboration between

Members States if necessary) and used as a basis for identifying and planning required connectivity conservation and restoration measures.

5) **Have scientific studies indicated that the species is vulnerable to changes in suitable climate space (e.g. there is likely to be little overlap between the current and future projected ranges)?**

Although the species is unlikely to be vulnerable to habitat fragmentation, we need to know whether the effects of climate change are going to act synergistically with fragmentation and potentially exacerbate fragmentation impacts and constrain climate change adaptation.

5.1 **If YES**: Go to Step 7.
5.2 **If NO:** Go to Step 6.

6) **Is the species at risk from changes in climate space according to an assessment of the following vulnerability traits?**

Using existing knowledge assess the species' climate change vulnerability traits against the risk categories in Table 3.

Table 3. Climate space change risk categories associated with species' traits

TRAITS	**RISK**		
	LOW	**MEDIUM**	**HIGH**
POSITION ON TEMPERATURE GRADIENT	HIGH	MEDIUM-LOW	LOW
DEVIATION FROM MEAN PRECIPITATION	LOW	MODERATE	HIGH, E.G. MOIST/WET, ARID HABITATS
MEAN ALTITUDE	LOW	MEDIUM	HIGH
NICHE BREADTH	BROAD (GENERALIST)	NARROW (SPECIALIST)	NARROW (SPECIALIST)
RANGE SIZE	LARGE	SMALL	SMALL

Does the species fall within the medium or high risk category for 2 or more of the traits?

5.1 **If YES**: The species is at risk from changes in climate space. Go to Step 7.
5.2 **If NO:** The species is unlikely to be of immediate concern from fragmentation and changing climatic conditions. Therefore other species should be considered as priorities for connectivity conservation and an assessment of connectivity requirements is not required at the moment. However, the species should be re-

evaluated at appropriate timescales and immediately if new information becomes available that is likely to change the species' assessment.

7) **Carry out a detailed connectivity needs assessment in relation to climate change adaptation requirements**

   Although the species does not appear to be impacted by, or vulnerable to, habitat fragmentation at the moment, this may change as a result of the effects of climate change on the species. Existing and potential fragmentation may also constrain the species' ability to adapt to climate change impacts. The assessment should therefore focus on the potential synergistic impacts of climate change and fragmentation on the species. The assessment should be carried out at an appropriate biogeographical scale (through collaboration between Members States if necessary) and be used as a basis for identifying and planning required connectivity conservation and restoration measures.

Risk assessment examples

Table 4 provides a worked example of the application of the fragmentation and climate space risk assessments outlined in Tables 2 and 3. These include a selection of species that were studied as part of the Modelling Natural Resource Responses to Climate Change (MONARCH) project in the UK (Walmsley et al 2007). Data concerning the habitat fragmentation sensitivity traits and the climate associations are included for comparison.

For species projected to gain habitat in the UK under climate scenarios (Table 4a), Stone Curlew (*Burhinus oedicnemus*) and the Heath Fritillary (*Mellicta athalia*) would be of concern from a fragmentation perspective, but the climate associations indicate that all species should prosper under climate change. Both bird species were identified in the supporting analysis for this guidance as having a low vulnerability to changes in their climate envelopes (see earlier sections).

For species projected by the MONARCH project to lose climate space (Table 4b), both the Black Grouse (*Tetrao tetrix*) and the Twinflower (*Linnaea borealis*) are at high risk according to several fragmentation and climate change vulnerability traits. In contrast, the Song Thrush (*Turdus philomelos*) is currently a widely dispersed species which appears to be at low risk from fragmentation and climate space changes. However, according to the MONRCH results it is projected to lose suitable climate space due to the effects of warmer summers and agricultural practices on prey species (Walmsley et al 2007).

Table 4. Fragmentation risk categories associated with species traits

Trait risk categories are indicated as follows: High risk = Red fill, bold and capitals; Moderate risk = orange fill and underlined; Low risk = Green fill and normal type. SPEC = Species of European Conservation Concern (BirdLife International 2004).

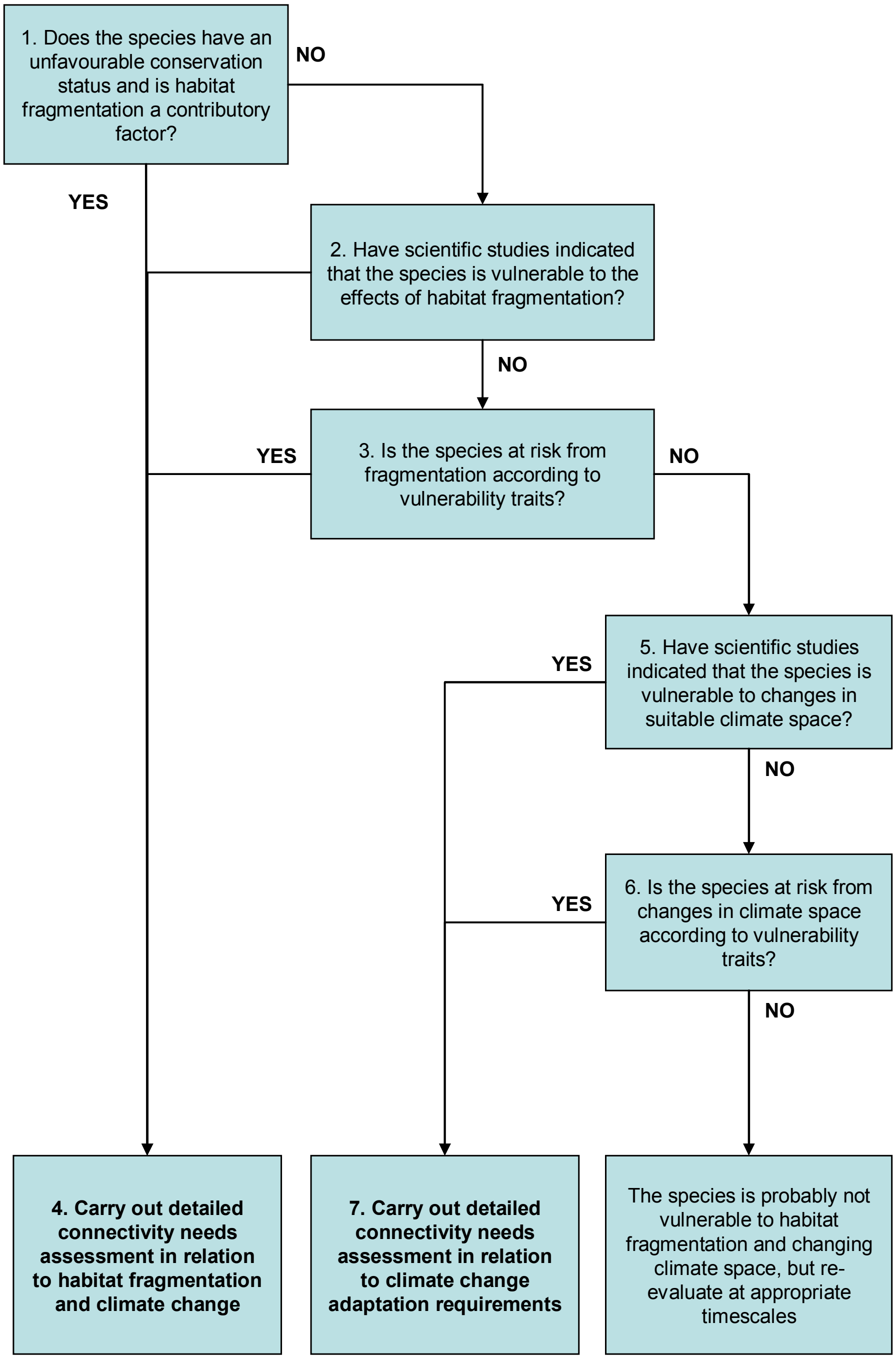
a.

	SPECIES		
	STONE CURLEW *BURHINUS OEDICNEMUS*	CORN BUNTING *MILIARIA CALANDRA*	HEATH FRITILLARY *MELLICTA ATHALIA*
MONARCH PROJECTION	GAIN	GAIN	GAIN
FRAGMENTATION VULNERABILITY TRAITS			
CONSERVATION STATUS	**SPEC 3/ANNEX 1**	**SPEC 2/ANNEX 1**	
ABUNDANCE	**LOW**	**LOW**	HIGH
INDIVIDUAL AREA REQUIREMENT	**HIGH**	LOW	LOW
NICHE BREADTH (HABITAT SPECIFICITY)	**NARROW**	BROAD	**SPECIFIC**
DISPERSAL ABILITY/MOBILITY	HIGH	HIGH	**LOW (NORMALLY LESS THAN 100M)**
REPRODUCTIVE POTENTIAL	**LOW**	HIGH	**LOW (SINGLE BROOD)**
POPULATION FLUCTUATION	LOW	LOW	LOW
CLIMATE CHANGE VULNERABILITY TRAITS			
POSITION ON TEMPERATURE GRADIENT	WARM	AVERAGE-WARM	AVERAGE
DEVIATION FROM MEAN PRECIPITATION	MODERATE (ARID)	AVERAGE	AVERAGE
MEAN ALTITUDE	LOW	LOW	AVERAGE
NICHE BREADTH	**NARROW**	BROAD	**SPECIFIC**
RANGE SIZE	HIGH	HIGH	HIGH

b.

	SPECIES		
	BLACK GROUSE ***TETRAO TETRIX***	**SONG THRUSH** ***TURDUS PHILOMELOS***	**TWINFLOWER** ***LINNAEA BOREALIS***
MONARCH PROJECTION	LOSS	LOSS	LOSS
FRAGMENTATION VULNERABILITY TRAITS			
CONSERVATION STATUS	**SPEC 3/ANNEX 1**	NON-SPEC	
ABUNDANCE	**LOW**	HIGH	**LOW**
INDIVIDUAL AREA REQUIREMENT	**HIGH**	MODERATE	LOW
NICHE BREADTH (HABITAT SPECIFICITY)	**SPECIALIST**	GENERALIST	**SPECIALIST**
DISPERSAL ABILITY/MOBILITY	HIGH	HIGH	**LOW**
REPRODUCTIVE POTENTIAL	**LOW**	HIGH	**LOW**
POPULATION FLUCTUATION	?	LOW	?
CLIMATE CHANGE VULNERABILITY TRAITS			
POSITION ON TEMPERATURE GRADIENT	**COLD**	AVERAGE	**COLD**
DEVIATION FROM MEAN PRECIPITATION	MODERATE	MODERATE (MOIST AREAS)	MODERATE (SHALLOW ROOTED NEEDS MOIST AREAS)
MEAN ALTITUDE	AVERAGE TO HIGH	LOW	**HIGH**
NICHE BREADTH	**SPECIALIST**	GENERALIST	**SPECIALIST**
RANGE SIZE	**LOW**	HIGH	

Figure 4. Framework for fragmentation and climate change risk assessment



4.3 Conclusions

In this section we have reviewed some of the leading literature concerning traits that may species more vulnerable to the synergistic effects of climate change and habitat fragmentation. We have identified a subset of these traits and propose a simple methodology to give preliminary estimates of whether certain taxa may be vulnerable or not. Within the scope of this limited study we have used climate envelope data for all European breeding birds to identify whether the top 50 vulnerable species in terms of climate space exhibit the traits identified. Our results indicate that there was wide variation in the expression of traits as would be expected. These traits were also subjectively measured, and it would be possible to debate the justification for some (for example migratory status which was used as a proxy for dispersal ability). However the majority of the species showed two or more of the traits, and we think that this warrants more detailed attention.

We then developed a methodology to assess the risk faced by species from habitat fragmentation and climate change. The framework is designed to be a practical approach to identify those species that warrant immediate and detailed attention. It is also designed to be used in the presence or absence of scientific data concerning the species in question. As with other links between the impacts of climate change and habitat fragmentation on species, the mediating effects of traits and associations requires more detailed research.

5. REPORT CONCLUSIONS

It is clear that habitat destruction is the leading threat facing biodiversity at the moment. Habitat loss is usually not a uniform process, instead areas of suitable habitat are converted at different rates to other forms of land use. Therefore as habitats are lost, they become fragmented – with patches being reduced in size and becoming more isolated. It is important to separate the loss of habitat as an end result from the process of habitat fragmentation. Fragmentation is a spatially explicit and scaled process and therefore considering the impacts and responses of species requires a landscape (or at least spatial) perspective. When considering fragmentation as a process alone, i.e. by controlling for the impacts of habitat loss, it thought that the impacts are only expressed when there is little remaining habitat (<30%; Fahrig 2003). Fragmentation can also be a natural process and many species have evolved to cope in naturally fragmented habitats. There is a broad literature that describes the impacts of habitat loss and to a lesser extent fragmentation on species. These studies highlight that species have variable responses and that these responses are mediated through a series of traits that can limit or exacerbate the effects of fragmentation. However less research attention has been paid to studying the role of species traits in observed responses to fragmentation in controlled or experimental settings; leaving some assumptions concerning which traits are important untested. Also results from different species or even the same species in different conditions can be contradictory. In this study we have reviewed some of the main impacts of habitat fragmentation and have developed a list of traits that are identified within the literature as mediating species responses.

There is now a strong body of evidence to show that species are responding to climate primarily through phenological or range changes. In general this means that life history events occur earlier in the year and species distributions are moving further north. Currently it is difficult to generate landscape level predictions concerning the impacts of climate change, and further research is required to link models designed for specific regions to high-level models predicting continental scale changes. Although there is considerable regional variation, Europe is likely to experience warming in excess of the global mean, and this will exert greatest pressure on the northerly and southerly extremes of the continent. Species that have the centre part of their range towards the extremes of either mean temperature or precipitation are therefore more likely to be impacted by climate change. Also species that occur at high altitudes are also more vulnerable.

Based on the literature review and the models undertaken we suggest that a species' overall vulnerability to the synergistic effects of climate change and fragmentation can be assessed with a two stage process. The first stage asks whether, in the absence of existing knowledge, the species shows a series of traits that is likely to make it more vulnerable to fragmentation. Then the second stage asks whether this vulnerability is likely to be exacerbated by the effects of climate change. Our pilot test on birds showed that a simple measure of range size or even country presence, may give a good first indication of sensitivity to climate change induced range change. This crude measure may function less well for species that are highly localised or have very large ranges with significant regional variation, for example the wolf (*Canis lupus*). This simple hierarchical framework should allow the rapid identification of species of concern in the absence of existing scientific data. As a next step we suggest that these attributes are used to develop a quantitative score of vulnerability to climate change and fragmentation that is comparable across taxa.

Finally we recognise that species traits interact with each other in complex ways (Davies et al 2004) to express a response to habitat fragmentation that can change in different ecological settings. Therefore we would recommend more attention be paid to possible functional types that respond to fragmentation and climate change which embody a series of species traits. As a further step research should focus on the links between these functional types and different connectivity measures to provide more detailed recommendations concerning the most appropriate conservation actions for different functional types. These functional types will be scale dependent and connectivity measures must address this. This is a fruitful area of research where there are many open questions that have both scientific and applied outputs.

5.1 Recommendations

- Climate models are being developed for most taxonomic groups in Europe, but this should be completed for all groups and those species with smallest overlap between current future and present climate space should be identified, as we have achieved with European breeding birds. Climate models have been criticised for their lack of 'realism' with respect to tracking habitat conditions and projecting the ability of species to track change. However the techniques are developing rapidly and should be combined with extinction risk assessments.

- Increased research effort should be placed on species traits that may be used to identify their vulnerability to fragmentation and climate change. Research should identify whether a set of functional types can be developed based on groupings of these traits.

- In the absence of climate model techniques, we suggest that a rapid qualitative assessment based on a two stage process of first identifying species sensitive to habitat fragmentation and second determining whether this is likely to be exacerbated by sensitivity to climate change.

- Species assessments should be completed for all European taxonomic groups, such as IUCN Red List assessments, to collated required ecological data. These tools give the most effective measures of current extinction risk. Currently sufficient data exist for European birds and mammals.

- Longer term research is required to study the relationship between species from different taxonomic groups, their interactions with their habitats and the effects of changes to landscapes with climate change to develop a systematic tool to identify species at risk (Akçakaya et al 2006).

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TASK 1.2

Technical Annex: Assessing the requirement for range change

Report by Dr. Paul Donald (RSPB)
Climate Modeling by Prof. Rhys Green (Cambridge University/RSPB) and Prof. Brian Huntley (University of Durham)

SUMMARY

1. Task 1.1 reviewed the potential risks posed by habitat fragmentation to species attempting to adapt to climate change by tracking shifting climate envelopes. This report identifies European bird species that are likely to face the greatest need to track climate envelopes, and so for which fragmentation might pose the greatest threat in adapting to climate change.
2. A number of risk scores based on climate envelope models are presented. These scores relate only to the disparity between a species' current and projected climate envelopes, and do not reflect the relative vulnerability of species to other aspects of climate change.
3. Future climate space for birds listed on Annex I of the Birds Directive is not predicted to be smaller or larger, relative to current climate space, than for non-Annex I species, but climate space for Annex I species is projected to move more. Annex I species may therefore be more vulnerable to fragmentation than non-Annex I species.
4. A small number of species are predicted to lose all climate space in Europe. One of these, Berthelot's Pipit, is endemic to Europe.
5. Species whose populations are concentrated in Europe are predicted to lose less climate space and have lower overall risk scores than species that have larger populations outside Europe than within Europe.
6. Risk scores from models of different scenarios of climate change were strongly correlated with crude estimates of current distribution, suggesting that for species for which climate envelope data are not available, a crude measure of range is likely to be a strong correlate of its requirement to track moving climate space (even if simply estimated from the number of European countries it occurs in). Species with smaller ranges have higher risk scores, indicating a greater requirement to shift their ranges and so a potentially greater vulnerability to fragmentation.
7. Risk scores also differed significantly between species occupying different habitats and between species of differing migratory strategies.
8. The results suggest that a crude estimate of range size might provide an index of risk from climate-change induced range change for the many plant and animal species in Europe for which climate envelope models are not available. Such an index could provide a useful first filter in identifying species for which conservation action is most necessary. Subjective scoring of these species on a number of other criteria, such as habitat and migratory strategy, might then be useful in identifying the subset that might benefit most from enhanced connectivity.

1. INTRODUCTION

The effects of global climate change are already being felt by wildlife, and a global 'fingerprint' of climate change is apparent (Parmesan & Yohe 2003, Root *et al.* 2003). However, predicting future changes is difficult and the impacts of climate change are unlikely to be monotonic. For example, butterfly populations are predicted to increase in range and population in the UK (Roy *et al.* 2001) but to decline in the Mediterranean (Stefanescu *et al.* 2004), and mammal and bird species richness are predicted to increase in cool mountainous areas of the USA but decline in southern areas (Currie 2001).

As discussed in Task 1.1 of this report, one of the main impacts of climate change on wildlife is likely to be a requirement for species to track shifting climate space. Altitudinal and latitudinal shifts in distribution have already been reported in butterflies (Parmesan *et al.* 1999, Konvicka *et al.* 2003), plants (Grabherr *et al.* 1994) and birds (Thomas & Lennon 1999, Hitch & Leberg 2007). Across a range of taxa, polewards shifts in range have occurred at an average rate of 6.1 km per decade(Parmesan & Yohe 2003). The ability of different species to track moving climate envelopes will depend at least in part on their ability to avoid becoming trapped in increasingly unsuitable areas. This requires that they have suitable habitat within not only their final projected ranges, but also within all parts of their transitional ranges. Fragmentation is likely to inhibit such movement, and it has been suggested that increasing habitat connectivity might help species to adapt to climate change(Collingham & Huntley 2000, Araujo *et al.* 2004, Hulme 2005, del Barrio *et al.* 2006, Donald & Evans 2006, Gaston *et al.* 2006, Davies & Pullin 2007).

The Quaternary record shows that range migration has been the usual response of organisms to climatic change (Huntley 1995, Currie 2001, Lyford *et al.* 2003), and such a response is likely to be repeated under future climate change (Collingham & Huntley 2000). Predictions of future change have so far been based largely on modelling the future distribution of species' current climate envelopes (Thomas *et al.* 2004, Araujo *et al.* 2006, Harrison *et al.* 2006). This climate envelope approach has been used to model distributional changes in a range of taxa in Europe (Thuiller *et al.* 2005, Araujo *et al.* 2006, Harrison *et al.* 2006, Huntley *et al.* 2006), Africa (Pearson *et al.* 2006, Thuiller *et al.* 2006) and the USA (Crumpacker *et al.* 2001) and extinction rates across a range of taxa globally (Thomas *et al.* 2004). Depending on the rate of climate change, an estimated 15-37% of species could become extinct by 2050 (Thomas *et al.* 2004), though such estimates need to be treated with caution (Lewis 2006, Schwartz *et al.* 2006).

Although current models of range change do not take account of changes in the distribution of habitats, food resources, predators etc., and assume no adaptation by species to novel climates, it is clear that climate alone is a major determinant of species distribution. For example, (Thuiller *et al.* 2004) suggested that the current distributions of plants, mammals and birds can be modelled so well with climate data alone that adding land cover variables to models does not greatly improve their predictive power. Similar conclusions were reached from modelling the distribution of birds in the Karoo biome of South Africa (Githaiga-Mwicigi *et al.* 2002). Climate envelope models appear to be useful predictors of range change across a wide range of taxa at different trophic levels (Huntley *et al.* 2004). However, predicting future ranges is an imprecise science (Pearson *et al.* 2006), and the use of climate-only models has come in for criticism (Woodward & Beerling 1997, Davis *et al.* 1998). There are a number of reasons for treating the results of climate-only models with caution. Simple laboratory experiments have suggested that species might change their distributions in unpredictable and sometimes counter-intuitive ways, and that present distributions are poor predictors of future distributions after climate change (Davis *et al.* 1998). Rates and patterns of dispersal, interactions with other animals whose ranges might change in different directions, trophic interactions, plasticity in response and availability and quality of habitat are all factors that can profoundly influence distributions that are not accounted for by climate-only predictions (Davis *et al.* 1998, Harrington *et al.* 1999). A further problem is that current ranges, which form the basis of such models, do not necessarily reflect only current conditions. For example, (Hawkins & Porter 2003) could detect a historical climatic signal that was 13,000 years old in the current distributions of birds and mammals in North America. Species may therefore persist in their current ranges long after their preferred climate envelope has moved elsewhere; both (Parmesan *et al.* 1999, Thomas & Lennon 1999) documented northwards extensions of the northern boundaries of the ranges of birds and butterflies that were not always accompanied by corresponding and predicted northward movements of their southern range boundaries. Therefore, while climate envelope models might reliably predict areas that may be colonised, they could overestimate extinction rates within existing ranges, at least within the short term. The available suitable climate space may perhaps best be regarded as representing a maximum potential future distribution, that is unlikely to be fully realized due to the operation of local factors and, more importantly, the need for species to disperse in order to fulfil parts of these new potential ranges (Pearson & Dawson 2003). Several dispersal models are now available (Carey 1996, Collingham *et al.* 1996, King & With 2002, Paradis *et al.* 2002) that could help predict the possibility of predicted climate envelopes being filled.

Climatic deterioration is likely to occur across part or all of the current ranges of a number of Europe's bird species. The demonstrated importance of climate in defining species' distribution suggests that the response of most species will be to colonise new areas as they become suitable and abandon ones where conditions deteriorate, leading to range shifts. Their ability to survive this transition depends mainly on the availability of suitable habitats within their transitional and new ranges and their ability to reach them. This in turn depends at least partly on landscape structure, and the potentially synergistic effects of landscape structure and climate change are important, though poorly understood (Honnay *et al.* 2002, Opdam & Wascher 2004). Suitable habitats might be patchily distributed across the landscape, particularly in regions like Western Europe, where a long history of agricultural industrialisation has fragmented natural habitats and made passage through the habitat matrix difficult (Thomas 2000, Donald & Evans 2006). This might limit the ability of species to move across a landscape in a series of colonisations and extinctions (Honnay *et al.* 2002, Higgins *et al.* 2003, Opdam & Wascher 2004). Climate change itself might cause additional fragmentation, for example through an increased frequency of large-scale habitat disturbances caused by extreme weather events, and effects of climate change and fragmentation are likely to be synergistic rather than additive (Opdam & Wascher

2004). (Shafer *et al.* 2001), for example, predicted that not only will the climate envelopes of many North American trees and shrubs move under current climate change predictions, but several of them will become increasingly fragmented.

The degree of threat from climate changed should be assessed not only on the basis of a species' current threat status but also on its life history characteristics, properties of the landscapes in which they live and the degree of difference between present and projected ranges (Akcakaya *et al.* 2006). In an analysis of over 1,000 species of European plants, (Thuiller *et al.* 2005) found a positive correlation between the proportion of climate space predicted from climate envelope models to remain and a species' niche position and breadth. Species with large current distributions and wide niche breadth were predicted to lose a lower proportion of climate space than range- or niche-restricted species.

Task 1.2 aims to support the risk assessment developed in Task 1.1 to develop a protocol for identifying species that might benefit most from improved habitat connectivity by (1) using the output from climate envelope models to identify the European bird species that will need to undertake the largest range changes to track their climate envelopes, (2) assessing whether species currently of high conservation concern are likely to be disproportionately affected by climate induced range change and (3) identifying characteristics of such species that could help assess the risk posed to species for which climate envelope models are not available.

2. METHODS

2.1 Climate Envelope Models

A description of the climate envelope models used is given in (Huntley et al. 2006). European distributions of all European bird species were available from the European Bird Census Council and were used to prepare the maps presented by Hagemeijer & Blair (1997). These data record the presence and absence of species breeding in Europe for the cells of a *c.* 50 km UTM grid. In addition, grid squares reporting neither presence nor absence were distinguished from those reporting absence, i.e. grid squares where the species was sought but not found. In modelling each species we used only those squares reporting presence or absence, although when simulating the species' present distribution we have extrapolated our model spatially to predict presence and absence of the species in 'no data' grid cells for which the climatic conditions fall within the range of climatic conditions to which the model is fitted.

For the European climate data, we interpolated monthly values of temperature, precipitation and insolation for the cells of the EBCC UTM grid from the 0.5° longitude × latitude global compilation of (New *et al.* 1999).

2.2 Models used

The modelling approach we used is that of fitting species–climate response surfaces that describe the probability of occurrence of a species throughout the space defined by a small number of bioclimatic variables (Huntley *et al.* 1995, Thompson *et al.* 1998) . We fitted these surfaces using locally weighted regression (Cleveland & Devlin 1988) because this makes no assumptions about the form of the relationship between a species' probability of occurrence and the bioclimatic variables. This approach also enables the surface to reflect the often complex interacting effects of the bioclimatic variables upon the species' distribution. This approach also requires an a priori decision as to which variables are to be included in the model. For European species we reasoned that winter cold, seasonal warmth and moisture availability were likely to be the primary determinants of species' distributions; these had already been shown to be important determinants both of individual plant and butterfly species' distributions in the region (Huntley *et al.* 1995, Hill *et al.* 2002) and of the potential broad-scale vegetation cover (Prentice *et al.* 1992). We experimented with alternative variables representing these three constraints, using them in combinations of three or four, in the latter case using two seasonal warmth variables, temperature sum and warmest month temperature. Although a few species were marginally better fitted by some other combination of variables, or by the addition of a fourth variable, the best-fitting model for the majority of species was obtained using the three variables, coldest month mean temperature, annual temperature sum above 5 °C and the annual ratio of actual to potential evapotranspiration (Huntley *et al.* 2006). Model fit was assessed using the area under the curve (AUC) for a receiver operating characteristic plot (Manel *et al.* 2001, Huntley *et al.* 2004), whilst for the purpose of representing the model results as simulations of species presence/absence the optimum threshold probability of occurrence was evaluated as that which optimized the value of Cohen's κ (Huntley *et al.* 1995). Models were considered to have a good fit if AUC ≥ 0.9.

2.3 Climate scenarios used

For our investigation of the potential impacts of projected 21st century climatic change upon European breeding birds we have chosen to focus primarily upon neither an 'optimistic' scenario, near the lower end of the range of projected warming, nor a 'pessimistic' scenario, near the upper end of the range, but have opted for a scenario derived from a simulation made used the Hadley Centre HadCM3 coupled atmosphere–ocean general circulation model (Gordon *et al.* 2000) using the B2 emissions scenario. HadCM3 is a grid model with a 3·75° longitude × 2·5° latitude spatial resolution. This model, in addition to being widely acknowledged as one of the leading models in the field, has an equilibrium climate sensitivity (i.e. the amount of warming simulated in response to a doubling of the concentration of carbon dioxide in the atmosphere) of 3·3°C that falls close to, but slightly below, the mean for the nine general circulation models (GCMs) included by the IPCC when making their ensemble projections (Cubasch *et al.* 2001). With respect to their simulations of global mean precipitation change, these models fall roughly into three groups of three: a 'high', a 'middle' and a 'low' increase group. HadCM3 is in the 'middle' group and simulates a mean increase in global precipitation that falls somewhat below the mean for the overall group of nine GCMs. Thus, the scenario that we primarily are considering is 'middle of the road' in quantitative terms for both temperature and precipitation. Qualitatively, the nature and direction of the projected climatic changes are, with few exceptions, generally consistent amongst the full range of GCMs included by the IPCC. Nonetheless, in order to explore the sensitivity of our results to the choice of GCM used, we also have developed and used two further scenarios; these are derived from the B2 emissions scenario simulations made using the ECHAM4/OPYC3 (Roeckner *et al.* 1996, hereafter referred to as ECHAM4) and GFDL_R30_c (Knutson *et al.* 1999, hereafter referred to as GFDL) GCMs. Both are spectral GCMs, ECHAM4 being a T42 model with an effective spatial resolution of 2·8° in both longitude and latitude, and GFDL being an R30 model with an effective spatial resolution of 3·75° longitude × 2·25° latitude. These models were chosen for this comparison because, whilst simulating a global mean warming similar to that simulated by the HadCM3 model, and thus near the mean value for the nine GCMs included by the IPCC in their ensemble syntheses, they are representative of the 'high' (GFDL) and 'low' (ECHAM4) groups with respect to their simulations of global mean precipitation increase (Cubasch *et al.* 2001).

2.4 Range change statistics

We calculated three measures of the projected impact of climate change on breeding range (see Fig. 1):

1. **Range ratio, R**. This is the number of UTM squares in the projected range divided by the number in the simulated recent range. A value less than 1 indicates that the projected range is smaller than the recent range. A value of zero indicates that the species has no projected range in Europe.
2. **Overlap, O**. This is the number of squares within the intersection between the projected and simulated recent ranges divided by the number of squares in the simulated recent range. This score is between zero and 1. A score of zero means that there is no overlap between the projected and recent ranges. A score of 1 indicates that all of the recent range remains suitable. However, if O = 1 and R > 1 there will also be some newly suitable range available, in addition to the recent range.
3. **Colonisation need, K**. This is the number of squares in the projected range, minus the number in the intersection of the projected and recent ranges, divided by the number of squares in the projected range. This score is between zero and 1. This represents the proportion of the projected range that is not currently in the simulated recent range. Note that this score cannot be calculated for species with R = 0. High scores indicate species in which realization of the projected future range depends largely on colonizing newly suitable areas.
4. **Overall risk scores**. We also calculated an overall risk score, based on a combination of these three measures. This followed the scoring of (Berry *et al.* 2006), who calculated two overall risk scores, one (**VA**) based on the assumption that species are unable to move into any new climate space and the other (**VB**) based on the assumption that all new climate space is occupied.

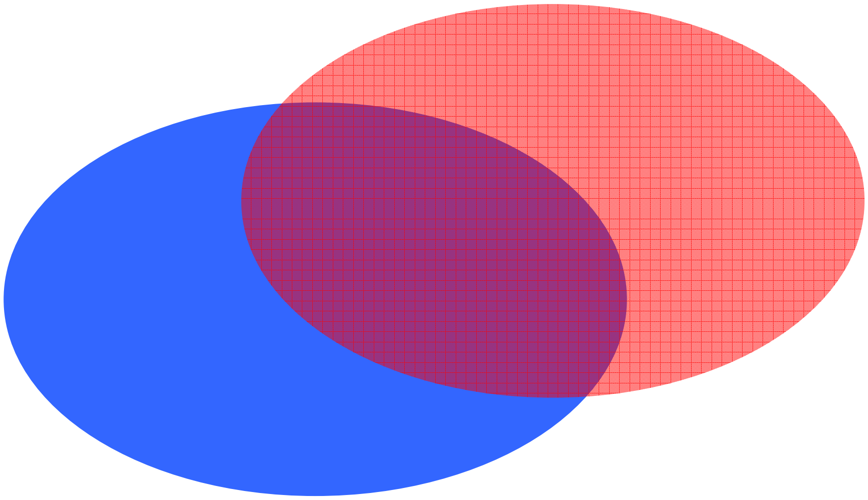
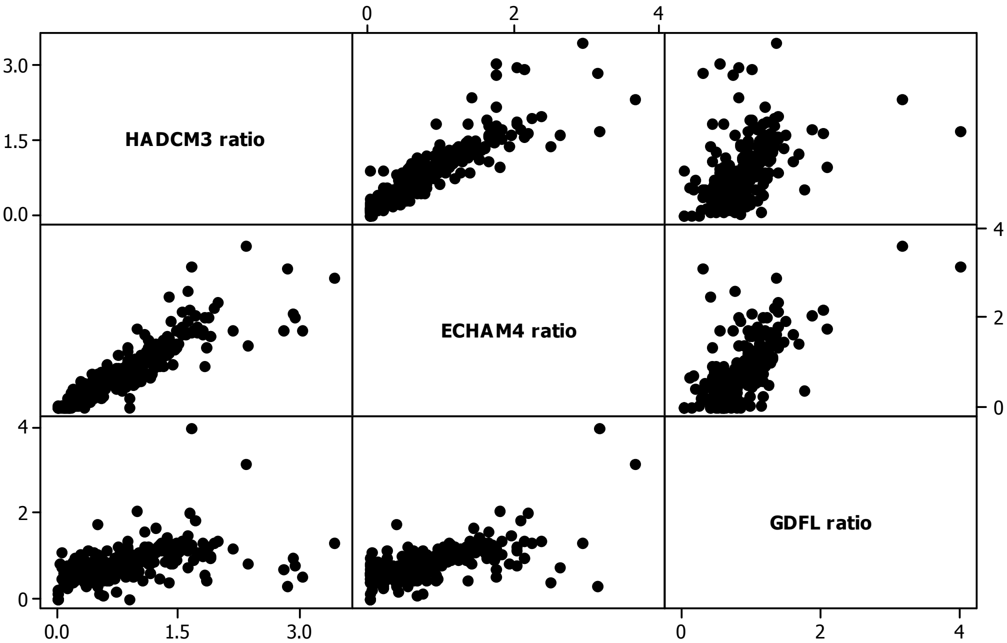


Fig. 1. Schematic diagram of the measures of impact of climate change on geographical distribution. The circle shaded blue and lilac represents the simulated recent range. The circle shaded flesh and lilac is the projected future range. The impact scores are: Range ratio R = (flesh+lilac)/(blue+lilac); Overlap O = lilac/(blue+lilac); Colonisation need K = flesh/(flesh+lilac).

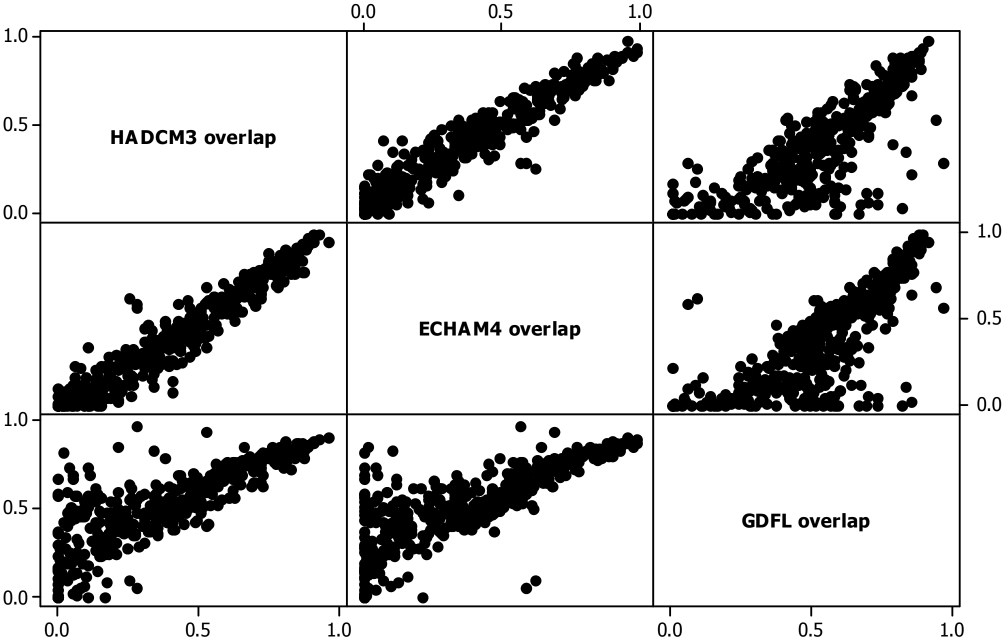
3. RESULTS

3.1 Risk scores

The estimates of Ratio, Overlap and Colonisation were strongly correlated between the three climate change scenarios (Fig. 2), so an average was calculated for each.



HADCM3 ratio
ECHAM4 ratio
GDFL ratio
0
2
4
3.0
1.5
0.0
4
2
0
4
2
0
0.0
1.5
3.0
0
2
4



HADCM3 overlap
ECHAM4 overlap
GDFL overlap
0.0
0.5
1.0
1.0
0.5
0.0
1.0
0.5
0.0
1.0
0.5
0.0
0.0
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1.0
0.0
0.5
1.0

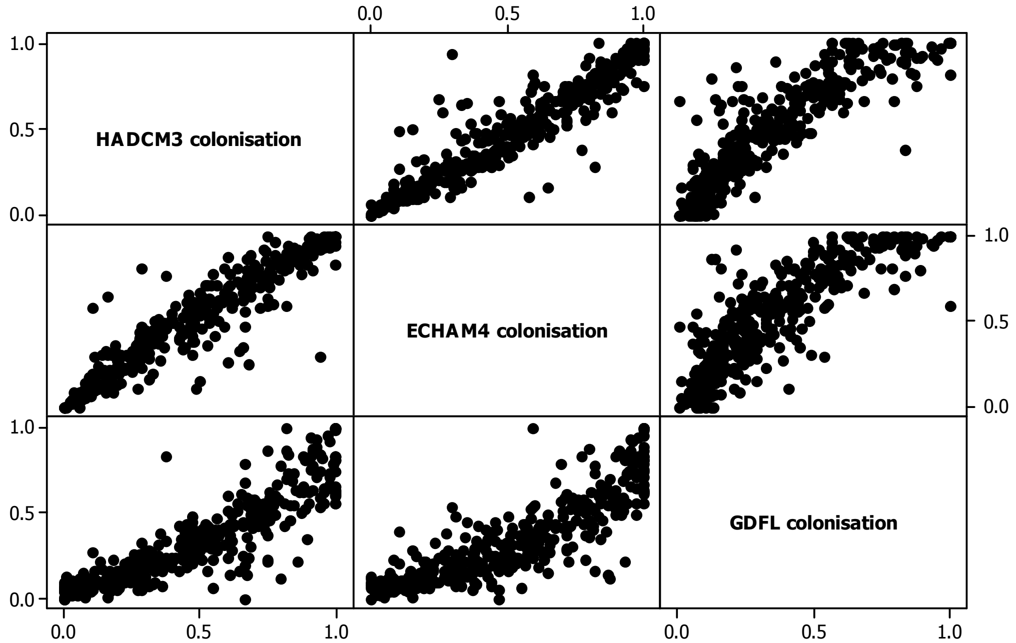

Fig. 2. Correlation matrix showing correlations across European bird species between scores for (i) Ratio, (ii) Overlap and (iii) Colonisation for the three climate change scenarios.

The overall risk scores VA and VB were strongly correlated with each other and with the three averaged indices Ratio, Overlap and Colonisation (Fig. 3).

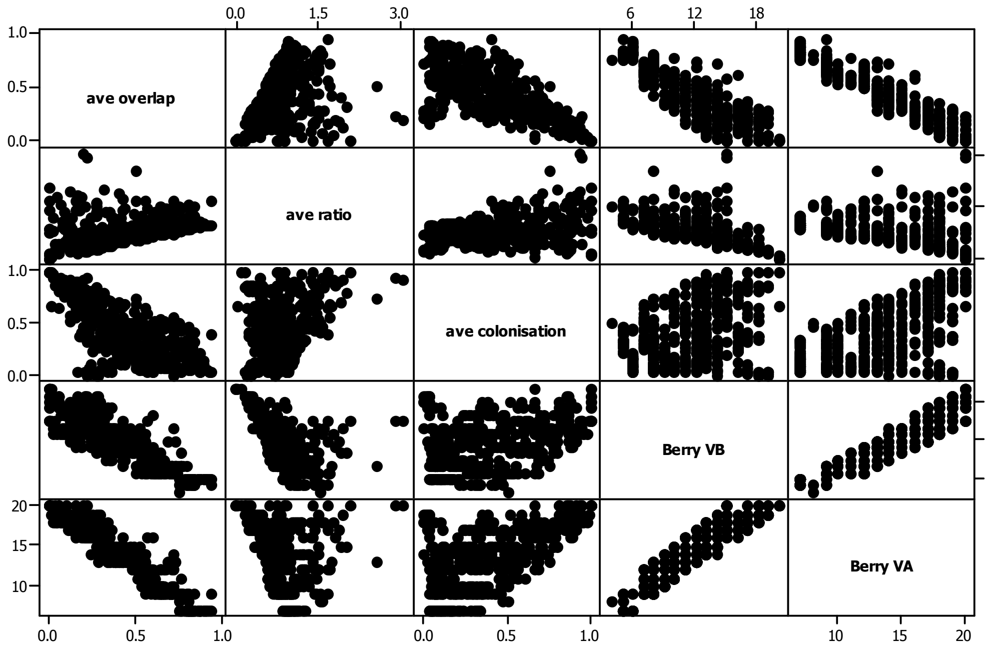

Fig. 3. Correlation matrix showing correlations across European bird species between scores for Ratio, Overlap and Colonisation averaged over the three climate change scenarios and the resulting measures of VA and VB.

3.2 Species with greatest changes in predicted climate space

Table 1 lists the 30 European bird species for which the ratio of projected range and modelled current range is lowest, those predicted to lose the highest proportion of current climate space. Table 2 lists the 30 European bird species for which the overlap between modelled current range and the projected future climate space is lowest. Table 3 lists the 30 European bird species for which the greatest movement from the current modelled range will be required to fill projected future climate space. Because there is a strong correlation between Ratio, Overlap and Colonisation (see previous section), several species appear in more than one table. Some species are predicted by models of one of more of the three climate change scenarios to have no remaining climate space in Europe, and thus are predicted to become extinct in Europe (Table 4). Most European bird species had values of Ratio of < 1, indicating that their projected climate space is smaller than their current estimated range sizes (Fig. 4).

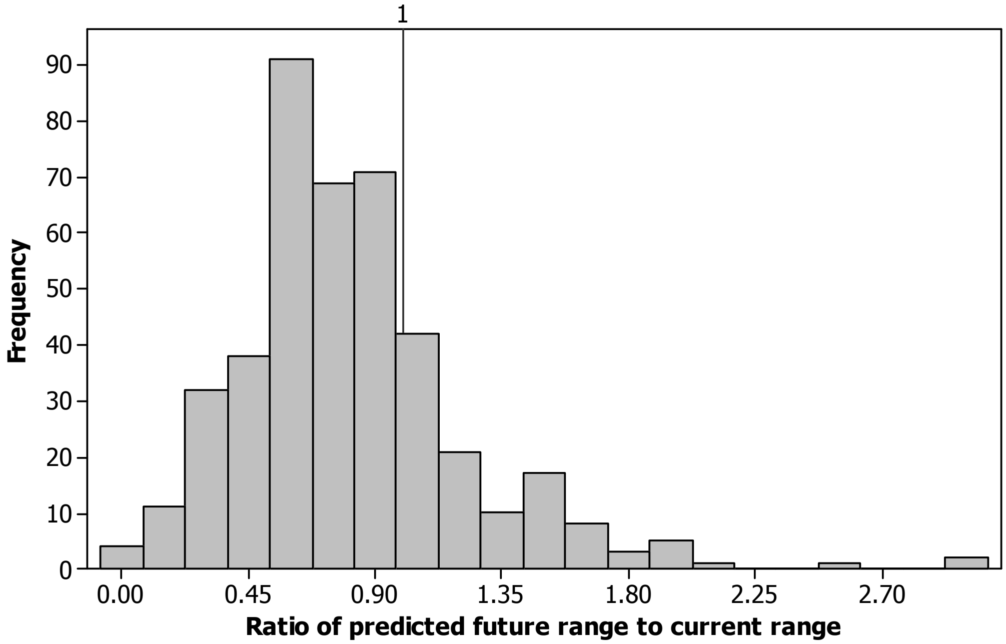

Fig. 4. Histogram of mean values of Ratio (R) for European bird species. All species with values less than 1.0 are expected to suffer an overall loss of climate space.

Species	Scientific name	Annex 1	Overlap	Ratio	Colonisation
Berthelot's Pipit	*Anthus berthelotii*	0	0.0000	0.0000	N/c
Dupont's Lark	*Chersophilus duponti*	1	0.0000	0.0000	N/c
Trumpeter Finch	*Rhodopechys githaginea*	1	0.0000	0.0000	N/c
Barbary Partridge*	*Alectoris barbara*	1	0.0123	0.0370	0.6700
White-headed Duck	*Oxyura leucocephala*	1	0.0000	0.0833	1.0000
Greater Flamingo	**Phoenicopterus ruber**	1	0.0000	0.1458	1.0000
Black-throated Accentor*	*Prunella atrogularis*	0	0.1624	0.1709	0.0278
Rosy Starling	*Sturnus roseus*	0	0.0546	0.1749	0.8551
Little Stint*	*Calidris minuta*	0	0.0524	0.1857	0.6592
Audouin's Gull	*Larus audouinii*	1	0.0523	0.2026	0.8730
Siberian Accentor*	*Prunella montanella*	0	0.2125	0.2125	0.0000
Siberian Rubythroat*	*Luscinia calliope*	0	0.2017	0.2133	0.0321
Lanceolated Warbler*	*Locustella lanceolata*	0	0.2146	0.2169	0.0059
Scaly Thrush*	*Zoothera dauma*	0	0.2104	0.2193	0.0236
Hoary Redpoll	*Carduelis hornemanni*	0	0.1212	0.2197	0.5200
Orange-flanked Bush-robin*	*Tarsiger cyanurus*	0	0.1748	0.2297	0.3766
Little Bunting*	*Emberiza pusilla*	0	0.1857	0.2367	0.4205
Great Black-headed Gull*	*Larus ichthyaetus*	0	0.0488	0.2439	0.8125
Red-throated Pipit	*Anthus cervinus*	0	0.2242	0.2440	0.0594
Dark-throated Thrush*	*Turdus ruficollis*	0	0.2403	0.2486	0.0213
Inornate Warbler*	*Phylloscopus inornatus*	0	0.2441	0.2512	0.0173
Olive-backed Pipit*	*Anthus hodgsoni*	0	0.2675	0.2675	0.0000
Yelkouan Shearwater	*Puffinus yelkouan*	1	0.0333	0.2778	0.8800
Pin-tailed Snipe*	*Gallinago stenura*	0	0.2805	0.2805	0.0000
Yellow-breasted Bunting*	*Emberiza aureola*	0	0.2451	0.2819	0.0978
Lesser White-fronted Goose	*Anser erythropus*	1	0.2680	0.2843	0.0219
Greater Spotted Eagle	*Aquila clanga*	1	0.1230	0.2861	0.5905
Bar-tailed Godwit	*Limosa lapponica*	1	0.1844	0.2891	0.3880
Tundra Swan	*Cygnus columbianus*	1	0.2811	0.2960	0.0288
Leach's Storm-petrel	*Oceanodroma leucorhoa*	1	0.0370	0.2963	0.8750

Table 1. The 30 species, Annex 1 (1) and non-Annex 1 (0) combined, predicted to undergo the greatest overall loss of climate space in Europe (Ratio), listed in increasing order of Ratio. Overlap and Colonisation scores are also given. Where total climate space is predicted to be lost under all three climate scenarios, Ratio = 0 and so the Colonisation score is not calculable (N/c). Species marked with an asterisk are only marginal breeders in Europe, breeding in fewer than 4 European countries and having the bulk of their world populations elsewhere.

Species	Scientific name	Annex 1	Overlap	Ratio	Colonisation
Dupont's Lark	*Chersophilus duponti*	1	0.0000	0.0000	N/c
Trumpeter Finch	*Rhodopechys githaginea*	1	0.0000	0.0000	N/c
White-headed Duck	*Oxyura leucocephala*	1	0.0000	0.0833	1.0000
Greater Flamingo	*Phoenicopterus ruber*	1	0.0000	0.1458	1.0000
White-rumped Swift*	*Apus caffer*	1	0.0000	0.8889	1.0000
Cinereous Bunting	*Emberiza cineracea*	1	0.0000	1.4167	1.0000
Krueper's Nuthatch	*Sitta krueperi*	1	0.0000	1.6667	1.0000
Scottish Crossbill	*Loxia scotica*	1	0.0000	2.0952	1.0000
Berthelot's Pipit	*Anthus berthelotii*	0	0.0000	0.0000	N/c
Sanderling	*Calidris alba*	0	0.0000	0.8750	1.0000
Azure Tit*	*Parus cyanus*	0	0.0000	0.7333	1.0000
Aquatic Warbler	*Acrocephalus paludicola*	1	0.0038	0.7879	0.9963
Barbary Partridge*	*Alectoris barbara*	1	0.0123	0.0370	0.6700
Rueppell's Warbler	*Sylvia rueppelli*	1	0.0226	0.8023	0.9467
Lanner Falcon	*Falco biarmicus*	1	0.0235	1.2019	0.9783
Mediterranean Gull	*Larus melanocephalus*	1	0.0275	0.4353	0.9468
Yelkouan Shearwater	*Puffinus yelkouan*	1	0.0333	0.2778	0.8800
Leach's Storm-petrel	*Oceanodroma leucorhoa*	1	0.0370	0.2963	0.8750
Masked Shrike	*Lanius nubicus*	1	0.0444	1.7778	0.9281
Great Black-headed Gull*	*Larus ichthyaetus*	0	0.0488	0.2439	0.8125
Lammergeier	*Gypaetus barbatus*	1	0.0508	0.3446	0.8645
Pallid Harrier	*Circus macrourus*	1	0.0513	0.4051	0.8750
Audouin's Gull	*Larus audouinii*	1	0.0523	0.2026	0.8730
Little Stint*	*Calidris minuta*	0	0.0524	0.1857	0.6592
Rosy Starling	*Sturnus roseus*	0	0.0546	0.1749	0.8551
Great Bustard	*Otis tarda*	1	0.0655	0.3175	0.8161
Moustached Warbler	*Acrocephalus melanopogon*	1	0.0671	1.5786	0.9547
Eurasian Spoonbill	*Platalea leucorodia*	1	0.0750	0.8958	0.9277
Demoiselle Crane*	*Grus virgo*	0	0.0769	0.4487	0.8894
Cinereous Vulture	*Aegypius monachus*	1	0.0805	1.0690	0.9153

Table 2. The 30 species, Annex 1 (1) and non-Annex 1 (0) combined, with the lowest degree of overlap between current modelled range and projected climate space, listed in ascending order of Overlap. Ratio and Colonisation scores are also given. Where total climate space is predicted to be lost under all three climate scenarios, Ratio = 0 and so the Colonisation score is not calculable (N/c). Species marked with an asterisk are only marginal breeders in Europe, breeding in fewer than 4 European countries and having the bulk of their world populations elsewhere.

Species	Scientific name	Annex 1	Overlap	Ratio	Colonisation
White-headed Duck	*Oxyura leucocephala*	1	0.0000	0.0833	1.0000
Greater Flamingo	*Phoenicopterus ruber*	1	0.0000	0.1458	1.0000
Azure Tit*	*Parus cyanus*	0	0.0000	0.7333	1.0000
Sanderling*	*Calidris alba*	0	0.0000	0.8750	1.0000
White-rumped Swift*	*Apus caffer*	1	0.0000	0.8889	1.0000
Cinereous Bunting	*Emberiza cineracea*	1	0.0000	1.4167	1.0000
Krueper's Nuthatch	*Sitta krueperi*	1	0.0000	1.6667	1.0000
Scottish Crossbill	*Loxia scotica*	1	0.0000	2.0952	1.0000
Aquatic Warbler	*Acrocephalus paludicola*	1	0.0038	0.7879	0.9963
Lanner Falcon	*Falco biarmicus*	1	0.0235	1.2019	0.9783
Moustached Warbler	*Acrocephalus melanopogon*	1	0.0671	1.5786	0.9547
Mediterranean Gull	*Larus melanocephalus*	1	0.0275	0.4353	0.9468
Rueppell's Warbler	*Sylvia rueppelli*	1	0.0226	0.8023	0.9467
Red-knobbed Coot*	*Fulica cristata*	1	0.2222	2.9444	0.9444
Marbled Teal	*Marmaronetta angustirostris*	1	0.1944	3.0556	0.9386
Spanish Imperial Eagle	*Aquila adalberti*	1	0.1232	1.9493	0.9384
Western Rock-nuthatch	*Sitta neumayer*	0	0.0822	1.3836	0.9384
Masked Shrike	*Lanius nubicus*	1	0.0444	1.7778	0.9281
Eurasian Spoonbill	*Platalea leucorodia*	1	0.0750	0.8958	0.9277
Cinereous Vulture	*Aegypius monachus*	1	0.0805	1.0690	0.9153
Marmora's Warbler	*Sylvia sarda*	1	0.0980	0.9085	0.9153
Wallcreeper	*Tichodroma muraria*	0	0.1648	1.8833	0.9111
Imperial Eagle	*Aquila heliaca*	1	0.0907	0.8730	0.9058
Yellow-billed Chough	*Pyrrhocorax graculus*	0	0.1487	1.6838	0.9048
Black-winged Kite*	*Elanus caeruleus*	1	0.1613	1.4301	0.8956
Squacco Heron	*Ardeola ralloides*	1	0.1240	1.1387	0.8942
Demoiselle Crane*	*Grus virgo*	0	0.0769	0.4487	0.8894
Alpine Accentor	*Prunella collaris*	0	0.1529	1.4060	0.8891
Rock Partridge	*Alectoris graeca*	1	0.1817	1.8314	0.8844
Gull-billed Tern	*Sterna nilotica*	0	0.1009	0.8991	0.8829

Table 3. The 30 species, Annex 1 (1) and non-Annex 1 (0) combined, with the highest predicted Colonisation scores, listed in decreasing order of Colonisation. Overlap and Ratio scores are also given. Species marked with an asterisk are only marginal breeders in Europe, breeding in fewer than 4 European countries and having the bulk of their world populations elsewhere.

	HADCM3	ECHAM4	GDFL
Dupont’s lark	X	X	X
Berthelot’s pipit	X	X	X
Trumpeter finch	X	X	X
White-headed duck	X		
Barbary partridge	X	X	
Pintail snipe		X	
Black-throated accentor		X	
Greater flamingo			
Lanceolated warbler		X	
White’s thrush		X	
Siberian rubythroat		X	
Bewick’s swan			
Olive-backed pipit		X	
Red-flanked bluetail		X	
Yellow-browed warbler		X	
Siberian accentor		X	
Dark-throated thrush		X	
Pallas’s gull		X	
Leach’s petrel		X	X

Table 4. Species predicted to lose all climate space in Europe under one or more of the three climate change scenarios. Species in italics are only marginal breeders in Europe

3.3 Species of high current conservation concern

Table 5 lists all European breeding birds listed by IUCN as Globally Threatened, together with their scores for Ratio, Overlap and Colonisation. Of the 10 species for which climate envelopes were modelled, three were expected to have increased climate space and seven reduced.

Species	Category	Overlap	Ratio	Colonisation
Lesser White-fronted Goose *Anser erythropus*	VU	0.268	0.284	0.022
Red-breasted Goose *Branta ruficollis*	VU		Not modelled	
Marbled Teal *Marmaronetta angustirostris*	VU	0.194	3.056	0.939
Steller's Eider *Polysticta stelleri*	VU		Not modelled	
White-headed Duck *Oxyura leucocephala*	EN	0.0	0.083	1.0
Zino's Petrel *Pterodroma madeira*	EN		Not modelled	
Balearic Shearwater *Puffinus mauretanicus*	CR		Not modelled	
Northern Bald Ibis *Geronticus eremita*	CR		Not modelled	
Dalmatian Pelican *Pelecanus crispus*	VU		Not modelled	
Lesser Kestrel *Falco naumanni*	VU	0.669	1.258	0.451
Saker Falcon *Falco cherrug*	EN	0.108	0.651	0.840
Greater Spotted Eagle *Aquila clanga*	VU	0.123	0.286	0.590
Spanish Imperial Eagle *Aquila adalberti*	VU	0.123	1.949	0.938
Imperial Eagle *Aquila heliaca*	VU	0.091	0.873	0.906
Great Bustard *Otis tarda*	VU	0.066	0.318	0.816
Houbara Bustard *Chlamydotis undulata*	VU		Not modelled	
Siberian Crane *Grus leucogeranus*	CR		Not modelled	
Sociable Lapwing *Vanellus gregarius*	CR		Not modelled	
Slender-billed Curlew *Numenius tenuirostris*	CR		Not modelled	
White-tailed Laurel Pigeon *Columba junoniae*	EN		Not modelled	
Aquatic Warbler *Acrocephalus paludicola*	VU	0.004	0.788	0.996
Fuerteventura Chat *Saxicola dacotiae*	EN		Not modelled	
Azores Bullfinch *Pyrrhula murina*	CR		Not modelled	

Table 5. All IUCN globally threatened species (GTS) that breed in Europe, giving estimates of Overlap, Ratio and Colonisation scores. A high proportion of these species breed in too few atlas squares in Europe to allow predictive modelling of their current or projected ranges. VU = Vulnerable, EN = Endangered, CR = Critically Endangered.

Overlap and Colonisation were significantly lower and higher respectively for Annex 1 species than for non-Annex 1 species, whereas Ratio did not differ significantly (Fig. 5). Future climate space for Annex I species is not therefore predicted to be relatively smaller or larger that the current modelled range size than is the case for non-Annex I species, but climate space is projected to move more. Annex I species may therefore be more vulnerable to fragmentation than non-Annex I species.

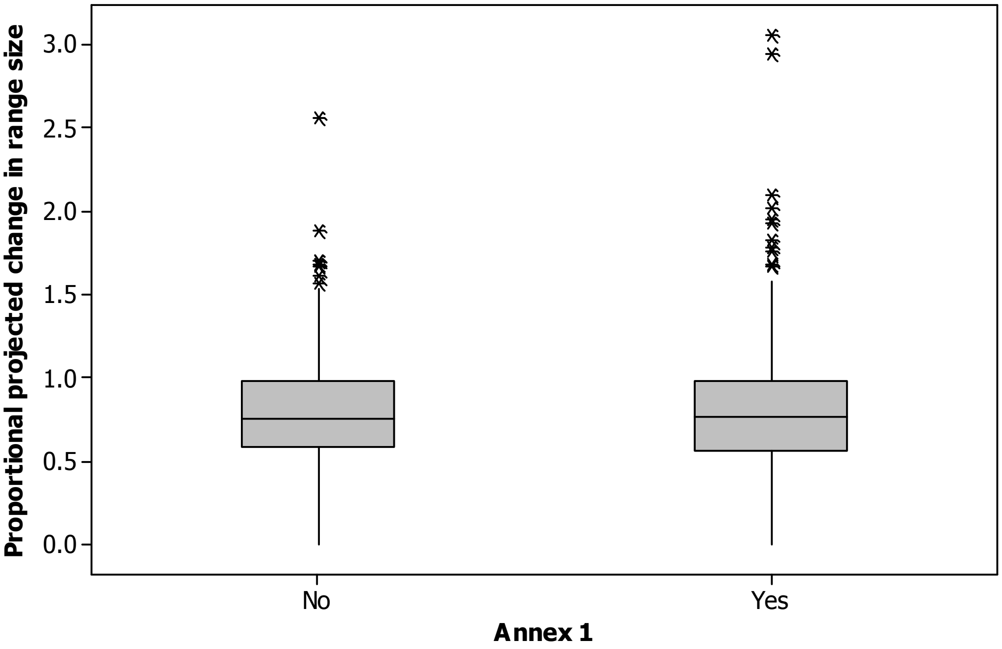

Fig. 5. Comparison between Annex I and non-Annex I species in the three measures Ratio (above), Overlap and Colonisation (both on next page). There was a significant difference between Annex I and non-Annex I species in Overlap and Colonisation ($P < 0.001$) but not in Ratio. Ratio, Overlap and Colonisation were averaged over three climate change scenarios.

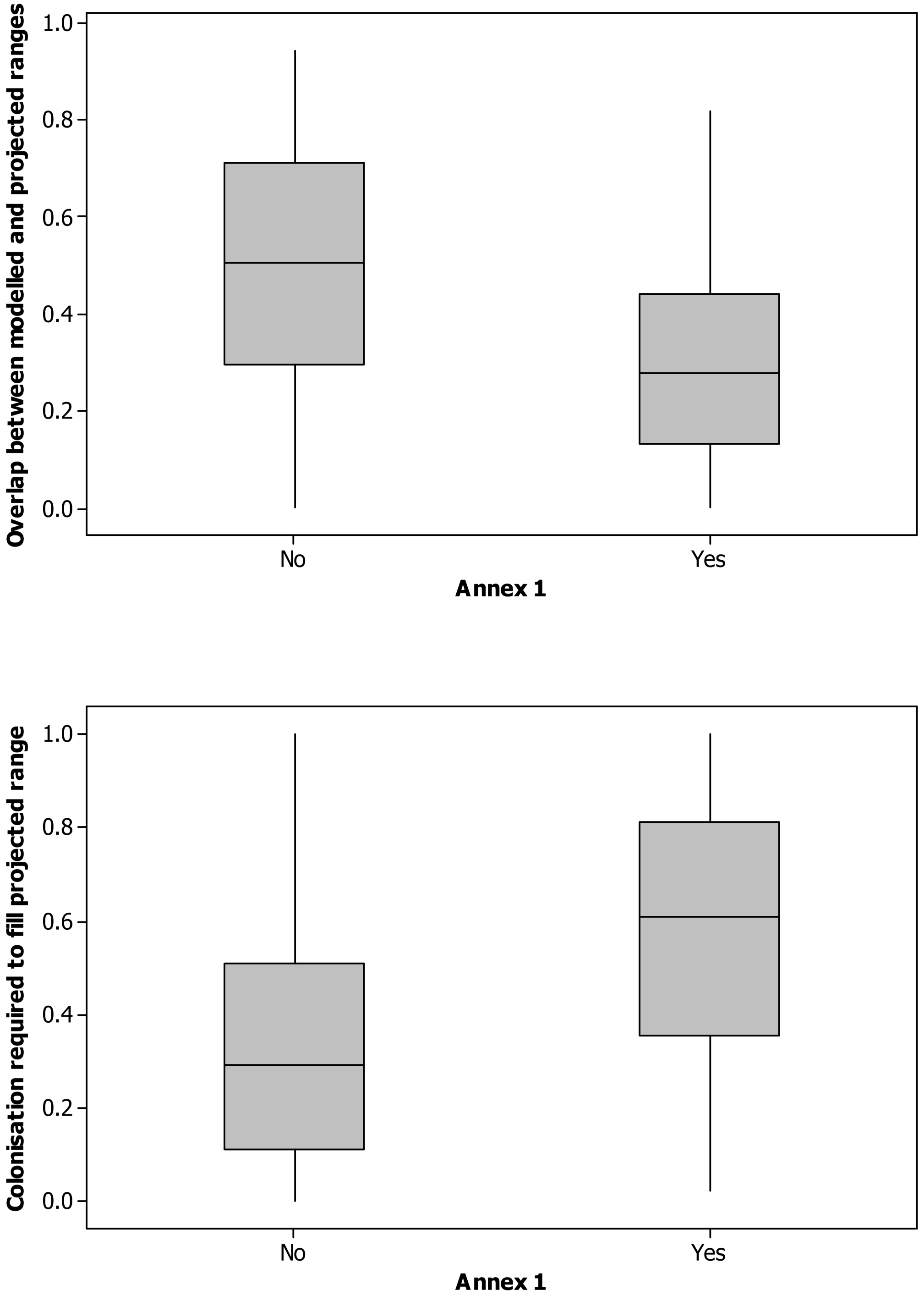
Overlap between modelled and projected ranges
1.0
0.8
0.6
0.4
0.2
0.0
No
Yes
Annex 1
Colonisation required to fill projected range
1.0
0.8
0.6
0.4
0.2
0.0
No
Yes
Annex 1

Fig. 5 (cont)

Table 6 lists the 30 European Annex I bird species for which the ratio of projected range and modelled current range is lowest, those predicted to lose the highest proportion of current climate space. Table 7 lists the 30 European Annex I bird species for which the overlap between modelled current range and the projected future climate space is lowest. Table 8 lists the 30 European Annex I bird species for which the greatest movement from the current modelled range will be required to fill projected future climate space. Because there is a strong correlation between Ratio, Overlap and Colonisation, several species appear in more than one table.

Species	Scientific name	Overlap	Ratio	Colonisation
Dupont's Lark	*Chersophilus duponti*	0.0000	0.0000	N/c
Trumpeter Finch	*Rhodopechys githaginea*	0.0000	0.0000	N/c
Barbary Partridge	*Alectoris barbara*	0.0123	0.0370	0.6700
White-headed Duck	*Oxyura leucocephala*	0.0000	0.0833	1.0000
Greater Flamingo	*Phoenicopterus ruber*	0.0000	0.1458	1.0000
Audouin's Gull	*Larus audouinii*	0.0523	0.2026	0.8730
Yelkouan Shearwater	*Puffinus yelkouan*	0.0333	0.2778	0.8800
Lesser White-fronted Goose	*Anser erythropus*	0.2680	0.2843	0.0219
Greater Spotted Eagle	*Aquila clanga*	0.1230	0.2861	0.5905
Bar-tailed Godwit	*Limosa lapponica*	0.1844	0.2891	0.3880
Tundra Swan	*Cygnus columbianus*	0.2811	0.2960	0.0288
Leach's Storm-petrel	*Oceanodroma leucorhoa*	0.0370	0.2963	0.8750
Snowy Owl	*Nyctea scandiaca*	0.2995	0.3143	0.0231
Great Bustard	*Otis tarda*	0.0655	0.3175	0.8161
Smew	*Mergellus albellus*	0.1721	0.3212	0.6674
Lammergeier	*Gypaetus barbatus*	0.0508	0.3446	0.8645
Great Grey Owl	*Strix nebulosa*	0.2637	0.3748	0.3060
Caspian Tern	*Sterna caspia*	0.1519	0.3882	0.5593
Terek Sandpiper	*Tringa cinerea*	0.2265	0.3948	0.4147
Barnacle Goose	*Branta leucopsis*	0.2906	0.4017	0.3791
Pallid Harrier	*Circus macrourus*	0.0513	0.4051	0.8750
Red-necked Phalarope	*Phalaropus lobatus*	0.3234	0.4172	0.2329
Mediterranean Gull	*Larus melanocephalus*	0.0275	0.4353	0.9468
Eurasian Griffon	*Gyps fulvus*	0.2402	0.4386	0.4690
Pied Avocet	*Recurvirostra avosetta*	0.1258	0.4400	0.7186
Cory's Shearwater	*Calonectris diomedea*	0.0826	0.4434	0.7728
Gyrfalcon	*Falco rusticolus*	0.3416	0.4509	0.2484
Whooper Swan	*Cygnus cygnus*	0.4309	0.4884	0.1174
Arctic Tern	*Sterna paradisaea*	0.4394	0.4936	0.1067
Eurasian Dotterel	*Eudromias morinellus*	0.2976	0.5019	0.4127

Table 6. The 30 Annex I species predicted to undergo the greatest overall loss of climate space in Europe (Ratio), listed in increasing order of Ratio. Overlap and Colonisation scores are also given. Where total climate space is predicted to be lost under all three climate scenarios, Ratio = 0 and so the Colonisation score is not calculable (N/c).

Species	Scientific name	Overlap	Ratio	Colonisation
White-rumped Swift	*Apus caffer*	0.0000	0.8889	1.0000
Dupont's Lark	*Chersophilus duponti*	0.0000	0.0000	N/c
Cinereous Bunting	*Emberiza cineracea*	0.0000	1.4167	1.0000
Scottish Crossbill	*Loxia scotica*	0.0000	2.0952	1.0000
White-headed Duck	*Oxyura leucocephala*	0.0000	0.0833	1.0000
Greater Flamingo	*Phoenicopterus ruber*	0.0000	0.1458	1.0000
Trumpeter Finch	*Rhodopechys githaginea*	0.0000	0.0000	N/c
Krueper's Nuthatch	*Sitta krueperi*	0.0000	1.6667	1.0000
Aquatic Warbler	*Acrocephalus paludicola*	0.0038	0.7879	0.9963
Barbary Partridge	*Alectoris barbara*	0.0123	0.0370	0.6700
Rueppell's Warbler	*Sylvia rueppelli*	0.0226	0.8023	0.9467
Lanner Falcon	*Falco biarmicus*	0.0235	1.2019	0.9783
Mediterranean Gull	*Larus melanocephalus*	0.0275	0.4353	0.9468
Yelkouan Shearwater	*Puffinus yelkouan*	0.0333	0.2778	0.8800
Leach's Storm-petrel	*Oceanodroma leucorhoa*	0.0370	0.2963	0.8750
Masked Shrike	*Lanius nubicus*	0.0444	1.7778	0.9281
Lammergeier	*Gypaetus barbatus*	0.0508	0.3446	0.8645
Pallid Harrier	*Circus macrourus*	0.0513	0.4051	0.8750
Audouin's Gull	*Larus audouinii*	0.0523	0.2026	0.8730
Great Bustard	*Otis tarda*	0.0655	0.3175	0.8161
Moustached Warbler	*Acrocephalus melanopogon*	0.0671	1.5786	0.9547
Eurasian Spoonbill	*Platalea leucorodia*	0.0750	0.8958	0.9277
Cinereous Vulture	*Aegypius monachus*	0.0805	1.0690	0.9153
Cory's Shearwater	*Calonectris diomedea*	0.0826	0.4434	0.7728
Semi-collared Flycatcher	*Ficedula semitorquata*	0.0870	1.1111	0.8676
Imperial Eagle	*Aquila heliaca*	0.0907	0.8730	0.9058
Marmora's Warbler	*Sylvia sarda*	0.0980	0.9085	0.9153
Glossy Ibis	*Plegadis falcinellus*	0.1068	0.7638	0.8787
Saker Falcon	*Falco cherrug*	0.1076	0.6510	0.8404
European Storm-petrel	*Hydrobates pelagicus*	0.1222	0.9778	0.8672

Table 7. The 30 Annex I species with the lowest degree of overlap between current modelled range and projected climate space, listed in ascending order of Overlap. Ratio and Colonisation scores are also given. Where total climate space is predicted to be lost under all three climate scenarios, Ratio = 0 and so the Colonisation score is not calculable (N/c).

Species	Scientific name	Overlap	Ratio	Colonisation
White-headed Duck	*Oxyura leucocephala*	0.0000	0.0833	1.0000
Greater Flamingo	*Phoenicopterus ruber*	0.0000	0.1458	1.0000
White-rumped Swift	*Apus caffer*	0.0000	0.8889	1.0000
Cinereous Bunting	*Emberiza cineracea*	0.0000	1.4167	1.0000
Krueper's Nuthatch	*Sitta krueperi*	0.0000	1.6667	1.0000
Scottish Crossbill	*Loxia scotica*	0.0000	2.0952	1.0000
Aquatic Warbler	*Acrocephalus paludicola*	0.0038	0.7879	0.9963
Lanner Falcon	*Falco biarmicus*	0.0235	1.2019	0.9783
Moustached Warbler	*Acrocephalus melanopogon*	0.0671	1.5786	0.9547
Mediterranean Gull	*Larus melanocephalus*	0.0275	0.4353	0.9468
Rueppell's Warbler	*Sylvia rueppelli*	0.0226	0.8023	0.9467
Red-knobbed Coot	*Fulica cristata*	0.2222	2.9444	0.9444
Marbled Teal	*Marmaronetta angustirostris*	0.1944	3.0556	0.9386
Spanish Imperial Eagle	*Aquila adalberti*	0.1232	1.9493	0.9384
Masked Shrike	*Lanius nubicus*	0.0444	1.7778	0.9281
Eurasian Spoonbill	*Platalea leucorodia*	0.0750	0.8958	0.9277
Cinereous Vulture	*Aegypius monachus*	0.0805	1.0690	0.9153
Marmora's Warbler	*Sylvia sarda*	0.0980	0.9085	0.9153
Imperial Eagle	*Aquila heliaca*	0.0907	0.8730	0.9058
Black-winged Kite	*Elanus caeruleus*	0.1613	1.4301	0.8956
Squacco Heron	*Ardeola ralloides*	0.1240	1.1387	0.8942
Rock Partridge	*Alectoris graeca*	0.1817	1.8314	0.8844
Yelkouan Shearwater	*Puffinus yelkouan*	0.0333	0.2778	0.8800
Glossy Ibis	*Plegadis falcinellus*	0.1068	0.7638	0.8787
Leach's Storm-petrel	*Oceanodroma leucorhoa*	0.0370	0.2963	0.8750
Pallid Harrier	*Circus macrourus*	0.0513	0.4051	0.8750
Audouin's Gull	*Larus audouinii*	0.0523	0.2026	0.8730
Pygmy Cormorant	*Phalacrocorax pygmeus*	0.1333	0.8848	0.8693
Semi-collared Flycatcher	*Ficedula semitorquata*	0.0870	1.1111	0.8676
European Storm-petrel	*Hydrobates pelagicus*	0.1222	0.9778	0.8672

Table 8. The 30 Annex I species with the highest predicted Colonisation scores, listed in decreasing order of Colonisation. Overlap and Ratio scores are also given.

3.4 Correlates of predicted range change

There was a highly significant correlation between overall risk scores (VA and VB) and current range size, assessed either from climate envelope models or from a crude estimate of the number of countries each species occurs in (Fig. 6).

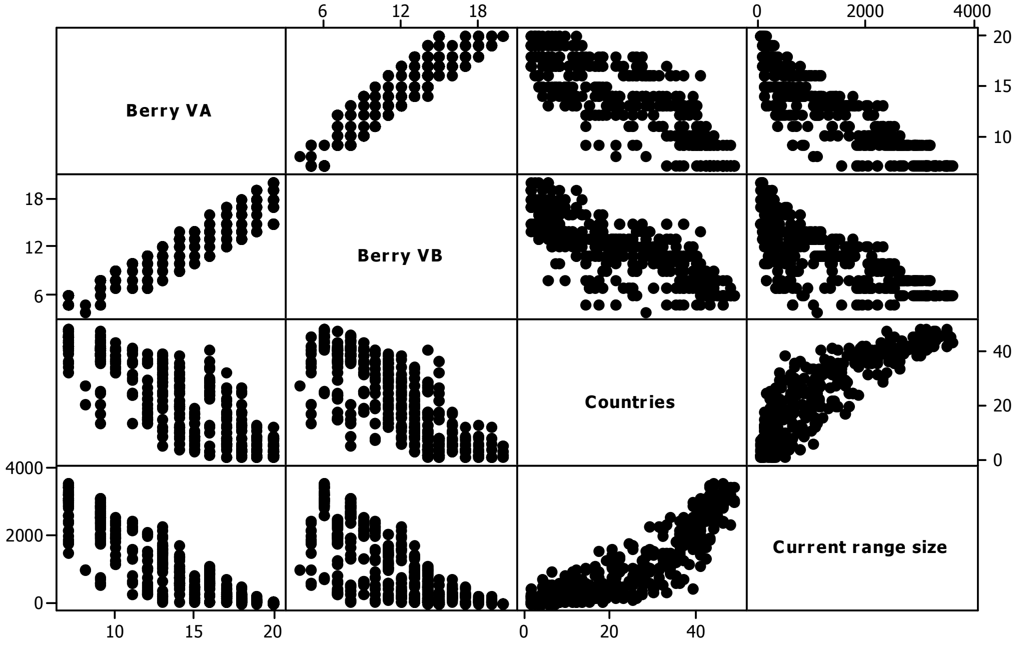

Fig. 6. Correlation matrix between two estimates of range size (current modelled range and the number of countries a species occurs in) and the two compound risk scores VA and VB.

Furthermore, VA and VB differed significantly between species occupying different habitats (Fig. 7) and species of different migratory status (Fig. 8).

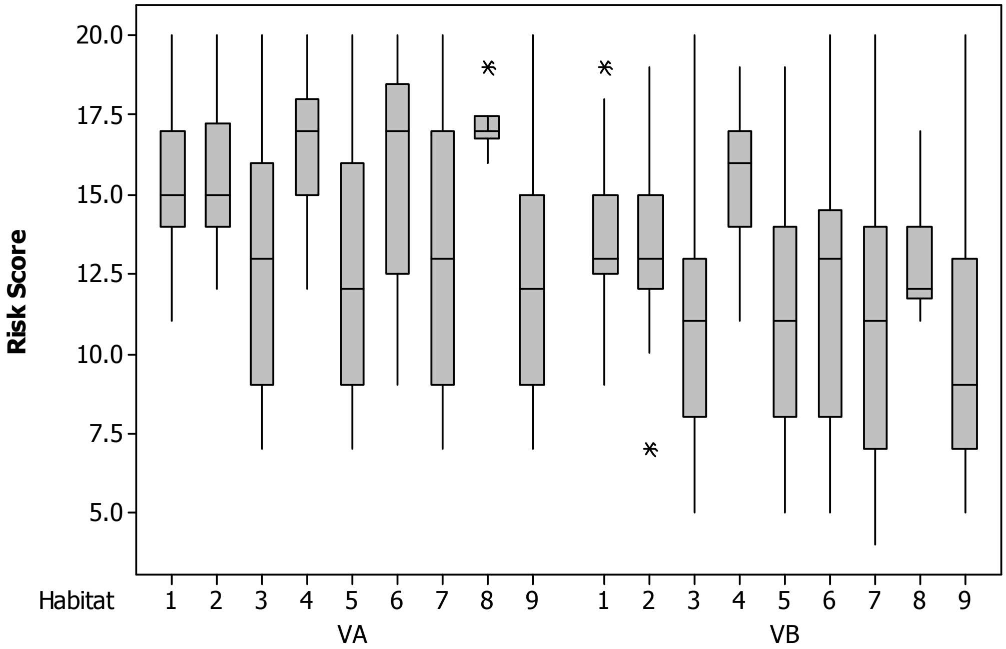

Fig. 7. Boxplots of risk scores VA and VB for birds in 9 habitat categories, allocated using methods in (Sanderson *et al.* 2006). 1 = marine, 2 = coastal, 3 = inland wetland, 4 = tundra, mires and moorland, 5 = boreal and temperate forests, 6 = Mediterranean habitats, 7 = agriculture and grassland, 8 = montane grassland, 9 = generalist. There was a significant difference between habitat classes for both risk scores (P < 0.001).

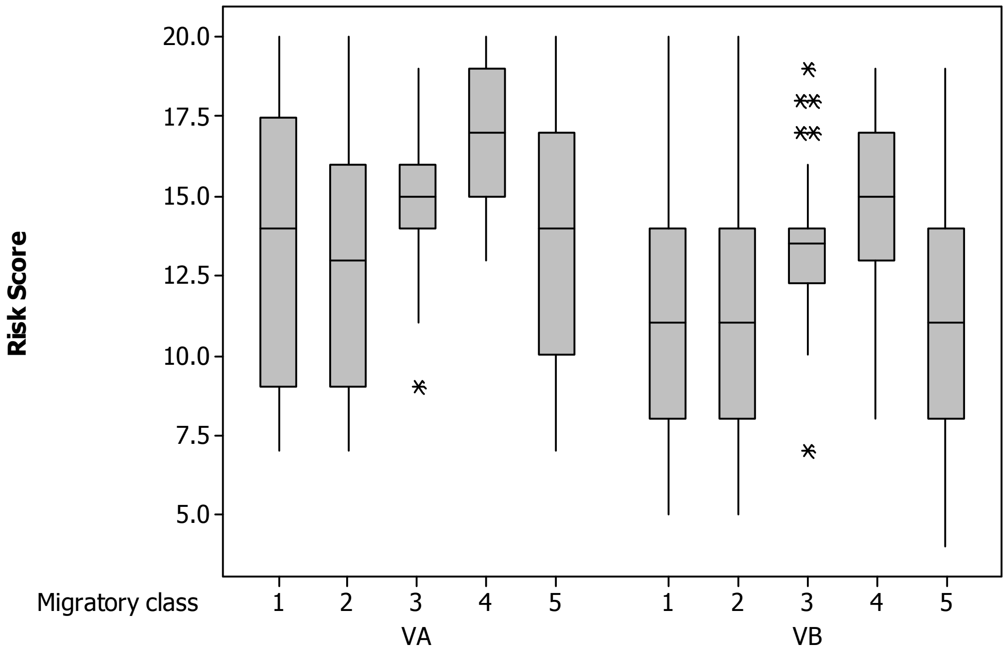

Fig. 8. Boxplots of risk scores VA and VB for birds in 5 migratory categories, allocated using methods in Sanderson et al. 2006. 1 = resident, 2 = partial migrant within Europe, 3 = migrant within Europe, 4 = short-distance migrant, 5 = long-distance migrant. There was a significant difference between migratory classes for both risk scores (P < 0.001).

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