Towards European climate risk surfaces: the extent and distribution of analogous and non-analogous climates 1931–2100

Ralf Ohlemüller1*, Emmanuel S. Gritti2, Martin T. Sykes2 and Chris D. Thomas1

ABSTRACT
Aim Climate is an important determinant of species distributions. We assess different aspects of risk arising from future climate change by quantifying changes in the spatial distribution of future climatic conditions compared with the recent past.

Location Europe.

Methods A 10’ × 10’ resolution gridded data set of five climate variables was used to calculate expected changes to the area, distance and direction of 1931–60 climatic conditions under the HadCM3 climate model for four future climate scenarios based on different rates of greenhouse gas emissions (SRES scenarios). Three levels of tolerance ranges determined the thresholds for which future conditions are considered analogous to 1931–60 (pre-warming) conditions.

Results For many parts of Europe, areas with pre-warming analogous climate conditions will be smaller and further away in the future than they are now. For any location in Europe, areas with pre-warming analogous mean annual temperature conditions will, on average, be reduced between 23.7% (B1 scenario) and 49.7% (A1FI scenario) by 2100 when assuming a medium tolerance range. The mean distance to these areas will, on average, increase between 272 km (B1) and 645 km (A1FI). These changes are more pronounced for temperature than for water availability variables and also for narrow tolerance ranges compared to wide tolerance ranges. Using a combined measure of both temperature and precipitation variables, areas with pre-warming analogous conditions are predicted to be in a more northeasterly direction in the future, but there are considerable regional differences within Europe.

Main conclusions The results suggest that, for some parts of Europe, the loss of area with any suitable climatic conditions represents the greatest risk to biodiversity, but in other regions the distances that species may have to move to reach suitable climatic conditions may be a greater problem. Quantifying the distance and direction in analyses of change of climatically suitable areas can add additional information for climate change risk assessments.

Keywords Climate change, climate space, Europe, GDD, habitat loss, HadCM3, precipitation, range, species distributions, temperature.

INTRODUCTION
Climate is one of the main determinants of species ranges and the distributions of many species are known to have changed with changing climate in the past (Huntley & Birks, 1983; McGlone et al., 2001; Mayle et al., 2004). Rates of anthropogenic global climate change in the recent past are reported to be faster than the natural rates of climate change of previous millennia (IPCC, 2001). Species responses to these recent changes, in the form of range shifts, are already apparent as so-called ‘fingerprints’ of anthropogenic climate change (Walther et al., 2002; Parmesan & Yohe, 2003; Hickling et al., 2005; Parmesan et al., 2005; Walther et al., 2005).

Assessment and predictions of risk for biodiversity arising from rapid anthropogenic climate change is usually based on
models projecting the potential distribution of a species under future climate scenarios (Sykes et al., 1996; Bakkenes et al., 2002; Berry et al., 2002; Thomas et al., 2004; Thuiller et al., 2005). Although this approach has helped to quantify and visualize potential ranges and extinction risk, there are a number of potential shortcomings and problems. First, only one component of risk (range size increase = low risk; range size decrease = high risk) is considered. A projected range size increase, however, does not necessarily imply low risk if the species has no chance of reaching the projected range area within the projected time frame. Similarly, the risk of projected range size decrease may be enhanced if the smaller projected range of a species is not only shrinking but also far away. Secondly, there are uncertainties associated with the choice of modelling method used to predict the potential future range of a species (Thomas et al., 2004; Thuiller, 2004). Different methods can result in considerable differences in the projected range size of a species under future climate scenarios (Thuiller, 2004). Finally, discrepancies between a species’ realized and fundamental climatic niche and the quality of large-scale species distribution data can lead to further uncertainties in predicting species ranges under future climate scenarios.

Thus, additional approaches to assess biological risk in the context of climate change are required. Such approaches can include methodologies that are more mechanistic and physiologically based, such as dynamic ecosystem models (e.g. Cramer et al., 2001 and references therein), although such approaches lack the species detail or the range of biota required for some studies. However, they can be complemented further by simple risk assessments based on individual species and biome modelling (e.g. Saxon et al., 2005). A major source of uncertainty is whether species will be able to disperse successfully to new areas of suitable climate space (Peterson et al., 2002; Thomas et al., 2004). Incorporation of dispersal into models of potential spread and distribution has advanced recently, but still suffers from many potential sources of uncertainty (Higgins et al., 2003); for example, due to lack of knowledge on dispersal distances for many species. Given the number of important ecological factors that will determine the responses of individual species to climate change, detailed modelling of the possible future responses of species is likely to be restricted to a small number of exemplary taxa. As such, more generalized risk assessment approaches are also desirable, to complement the detailed analyses of focal species.

Here, we present simple, species-independent analyses of climatic similarity in Europe under four different future climate scenarios to assess the amount and type of climatic risk that the biota as a whole may experience in different regions. We compare ‘pre-warming’ climatic conditions (average of 1931–60, referred to hereafter as ‘1945’) with current and future conditions. We identify and explore three measures of potential climatic risk for Europe’s biota based on the spatial distribution of observed and projected climate from 1931 to 2100: (1) the total land area and locations where 1945 climate conditions will have no analogue; (2) for locations where 1945-analogous climates will exist, how far a species would have to move in order to reach the nearest such location, and the average distance to all such areas; and (3) the direction in which areas with 1945-analogous climates are located under future climate scenarios. We then discuss three exemplar regions and show how different aspects of climate risk are prevalent in different parts of Europe.

**METHODS**

**Climate scenarios and variables**

We used observed and scenario climate data from the general circulation model HadCM3 at the scale of the ATEAM (http://www.pik-potsdam.de/ateam; accessed 15 January 2005) window (approx. 11° W, 35° N to 32° E, 72° N) with a 10’ resolution and four different emission scenarios: A1FI, A2, B2, B1 (Mitchell et al., 2004). The A1FI scenario describes a world with rapid economic development, an increase of population until 2050 followed by a decline thereafter and rapid introduction of new and more efficient technologies, but still with an emphasis on fossil fuel intensive uses. Between 2000 and 2100, the CO$_2$ atmospheric concentration is predicted to increase from 380 parts per million (p.p.m.) to 970 p.p.m. and global mean annual temperature is predicted to rise by 4.5 °C. The A2 scenario describes a heterogeneous world with regionally orientated economic development, a continuously increasing population and technological evolution slower and more fragmented than in other scenarios. According to this scenario, the CO$_2$ atmospheric concentration will increase from 380 p.p.m. to 860 p.p.m. between 2000 and 2100 and mean annual temperature will rise by 3.8 °C. The B1 scenario describes a convergent world with a rapid change towards a service and information economy, an increase of population until 2050 followed by a decline thereafter (as in A1FI), and the introduction of clean and resource-efficient technology. Between 2000 and 2100, the CO$_2$ atmospheric concentration is predicted to increase from 380 p.p.m. to 530 p.p.m. and mean annual temperature is predicted to rise by 2.0 °C. The B2 scenario describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. The population is increasing continuously (but at a lower rate than in A2) and the economic development is moderate with slower but more diverse technological evolution than in the B1 and A1FI scenarios. Between 2000 and 2100, the CO$_2$ atmospheric concentration is predicted to increase from 380 p.p.m. to 610 p.p.m. and mean annual temperature is predicted to rise by 2.7 °C (IPCC, 2001).

The HadCM3 general circulation model used assumes higher rates of climate change, for a given increase in atmospheric CO$_2$ concentration than other models (IPCC, 2001). However, within the HadCM3 model, the four emission scenarios used in the present study include the maximum and minimum projected CO$_2$ emission and temperature rise by 2100, giving some indication of the uncertainties associated with the climate predictions. For some of our analyses, we also present the results for two additional alternative general circulation models (CGCM2 and CSIRO2) in order to allow the reader to assess the differences between the three alternative models (Figs 1 and 2).

We used five temperature- and/or precipitation-based climate variables to characterize European climate space (Table 1). These variables have been used widely to model the potential distribution
of, among other biota, herbaceous plants, trees, mammals, reptiles, and birds in Europe (e.g. Sykes et al., 1996; Bakkenes et al., 2002; Berry et al., 2002; Thuiller, 2004):

1. Mean annual temperature \( [T_m (°C)] \) was calculated from monthly mean temperature values.

2. Monthly mean temperature of the coldest month per year \( [T_c (°C)] \) as a measure of winter cold and a surrogate for the absolute minimum temperature per year (Prentice et al., 1992; Sykes et al., 1996).

3. Annual growing degree days above 5 °C \( [GDD5 (°C \text{ year}^{-1})] \) as a measure of growing season warmth.

4. Annual precipitation \( [P_a \text{ (mm year}^{-1})] \) was calculated as the sum of monthly mean precipitation values per year.

5. Annual water deficit \( [P_d \text{ (mm year}^{-1})] \) was calculated as a simple measure of water availability (Leathwick et al., 2003) as:

\[
P_d = \sum_{i=1}^{12} (P_i - PET_i)[\text{for all } (P_i - PET_i) < 0, \text{ else let } (P_i - PET_i) = 0]
\]

with \( P_i \) = mean precipitation in month \( i \), \( PET_i \) = mean potential evapotranspiration in month \( i \)

\[
PET_i = \frac{(58.93 \times T_i)}{12} \left[ \text{if } T_i > 0 \text{ °C, } \text{else } PET_i = 0 \right]
\]

(following Skov & Svenning, 2004 and references therein).

\( T_i \) = mean temperature in month \( i \).

Although there are different and more sophisticated ways to calculate PET (e.g. Xu & Singh, 2000, 2002), this simple measure of PET was chosen here following its recent application in several large-scale, temperate vegetation analyses covering different climatic zones in Europe (Skov & Svenning, 2004; Svenning & Skov, 2004, 2005) and elsewhere (Lugo et al., 1999; Pan et al., 2003; Yang et al., 2002).

Climatic difference between time slices

The impact of anthropogenic warming on global climates is generally recognized as being evident from the 1970s onwards (IPCC, 2001). Therefore, we took the previous 1931–60 ‘climate-normal’ period (referred to here as the 1945- or pre-warming period) as our reference period and future changes are compared.
to mean values of the 1945 period. Because most current species distributions reflect historical, as much as current, climatic conditions, losing areas with pre-warming climatic conditions is therefore considered a risk to species.

In order to quantify climatic similarity between areas in Europe, we calculated the degree of climate change between the 1945 period and two subsequent observed (1961–90: \( t = 1975 \), 1991–2000: \( t = 1995 \)) and 10 projected time slices (2001–10: \( t = 2005 \), … , 2091–100: \( t = 2095 \)). Climatic distances \( \Delta C \) between climate conditions at cell \( i \) at \( t = 1945 \) and the climate conditions in every other cell \( j \) at \( t = 1945 \), 1975, 1995, 2005, … , 2095 were calculated for each of the five climate variables (\( C \)) as:

\[
\Delta C_{ij} = \sqrt{(C_{ij1945} - C_{ijt})^2}.
\]

We set three arbitrary tolerance ranges (\( TR \)): narrow, medium and wide (Table 1). A cell \( j \) in year \( t \) was considered 1945-analogous to cell \( i \) if \( \Delta C_{ij} \leq TR \). Accordingly, if \( \Delta C_{ij} > TR \), cell \( j \) in year \( t \) was considered not 1945-analogous to cell \( i \). For each grid cell \( i \), we determined all 1945-analogous cells for the different time slices using each of the four climate scenarios, each of the five climate variables and each of the three tolerance ranges. We performed this for each climate variable separately and for all five variables combined. In the latter case, a cell was considered not analogous to 1945 conditions if the difference between future and 1945 conditions for at least one of the five variables was greater than the tolerance range. For each grid cell, the total area with 1945-analogous climate conditions was determined by summing the area of all other cells with 1945-analogous conditions. Areas of grid cells were calculated taking into account the curvature of the earth.

**Geographic distance and direction**

Once all 1945-analogous cells \( j \) were determined for each cell \( i \), the geographical distance from cell \( i \) to each of the 1945-analogous cells \( j \) was calculated using great circle distance calculation following Zar (1989). For each grid cell we determined both the distance to the nearest grid cell with 1945-analogous conditions.
and the average distance to all 1945-analogous cells. In the majority of cases, the average distance was very similar to the median distance.

In order to account for edge effects caused by artificial boundaries of the study area in the east and south, cells for which the distance to the nearest 1945-analogous cell was larger than the distance between the cell and the nearest point of the artificial boundary of the study area were excluded from the analysis. For all other cells we calculated the average distance to the nearest 1945-analogous cell and the average distance to all 1945-analogous cells. To illustrate the changes in distance between our control period \( t = 1945 \) and future periods \( t = 1975, 1995, \ldots, 2095 \) at the given climatic change levels, we calculated the differences in distances between these time periods \( \Delta \text{km} = \text{km}_t - \text{km}_{1945} \) and plotted them against European average changes in the five climate variables \( \Delta T_m, \Delta T_c, \Delta \text{GDD5}, \Delta \text{Pa}, \Delta \text{Pd} \). The European averages are those given by the four emission scenarios for the 12 time slices up to 2100 (Mitchell et al., 2004). The direction from each cell \( i \) to each of the 1945-analogous cells \( j \) was expressed as the angle \( \alpha_{ij} \) from true north between cell \( i \) and cell \( j \) and calculated using great circle trigonometry following Zar (1989). The average of these angles was calculated using inverse tangent calculations (Batschelet, 1981).

### RESULTS

#### Total area with and without 1945-analogous conditions: mean annual temperature

For mean annual temperature, the total European land area without any 1945-analogous conditions elsewhere in Europe (for a medium tolerance range of \( \pm 1 \ ^\circ C \)) increases from zero in 1945 to c. 20,000 km\(^2\) (0.3% of European land area) for the B1 scenario or c. 320,000 km\(^2\) (4.9%) for the A1FI scenario by 2095 (Fig. 1a). The greatest areal increase in 1945 non-analogous conditions is predicted to happen in the second half of the 21st century. This increase is seen in all four scenarios but is most pronounced and accelerating under the A1FI and A2 scenarios. In 1945, on average each European grid cell shared 1945-analogous cells with a similar mean annual temperature (medium tolerance range) with an area of over 800,000 km\(^2\) (Fig. 1b). By 2095, this had declined to c. 600,000 km\(^2\) for the B1 scenario or c. 410,000 km\(^2\) for the A1FI scenario (Fig. 1b). All four scenarios predict the greatest losses in 1945-analogous areas to occur after 2030.

#### Distances to areas with 1945-analogous conditions: mean annual temperature

For any grid cell in Europe, the distance to the nearest grid cell with 1945-analogous mean annual temperature conditions is predicted to increase in the future (Fig. 2a). In 1945, the nearest 1945-analogous cell was on average an adjacent cell with an average distance of c. 10 km, whereas, by 2095, the nearest cell with 1945-analogous conditions is on average located c. 120 km (B1 scenario) to 280 km (A1FI scenario) away (using the medium tolerance range of \( \pm 1 \ ^\circ C \)). Similarly, for any location in Europe, we predicted an increase in the average distance to all grid cells with similar climate from c. 1000 km in 1945 to c. 1200 km (B1 scenario) or 1600 km (A1FI scenario) by 2095 (Fig. 2b). These 200–600 km shifts translate into migration rates of c. 1300 m year\(^{-1}\) (B1 scenario) to 4000 m year\(^{-1}\) (A1FI scenario) required to reach areas of 1945-analogous mean annual temperature conditions.

#### Change in other environmental variables

The other two temperature-based climate variables, \( T_c \) and GDD5, also showed a pronounced shift in extent between 1945 and 2095. In Fig. 3(a) \( (T_c) \), it can be seen that many grid squares had colder winters in 1945 than will occur anywhere in Europe in 2095 (B2 scenario; grey columns, with no corresponding open column), and that some regions will have warmer winters than occurred anywhere in Europe in 1945 (open columns, with no corresponding grey column). These represent non-analogue cold and warm winters, respectively. Variables based on temperature alone \( (T_m, T_c, \text{GDD5}) \) generate more non-analogue conditions than do variables based on precipitation \( (\text{Pd}) \) and precipitation and temperature \( (\text{Pd}) \) (Fig. 3a). Nonetheless, a substantial increase in water deficit is expected (negative \( \text{Pd} \) values), driven more by increased temperatures than by reduced precipitation (Fig. 3a). Both the change in average distance to the nearest and the change in average distance to all 1945-analogous cells between 1945 and the subsequent time slices is smaller for mean annual precipitation \( (\text{Pa}) \) and water deficit \( (\text{Pd}) \) than for the three temperature variables (Fig. 3b,c).
Increasing the tolerance range generally resulted in both smaller distances to the nearest and smaller average distances to all cells with 1945-analogous conditions, although the general trends remained consistent (Figs 2 and 3). By the time the European average mean annual temperature has changed by \( c. 7 ^\circ C \) compared to 1945 (the maximum increase predicted change by any scenario investigated here), the average increase in distance to the nearest cell with 1945-analogous conditions compared to 1945 is
c. 340 km for the narrow tolerance range and c. 200 km for the wide tolerance range (Fig. 3b). Minimum temperature (Tc) and growing degree days (GDD5) as well as annual water deficit (Pd) resulted in similar distances, whereas with an average change of 130 mm year\(^{-1}\) in mean annual rainfall (the maximum increase predicted by any scenario investigated here) this increase is only 90 km for the narrow and 30 km for the wide tolerance range (Fig. 3b).

Regional distribution of 1945-analogous conditions

The spatial distribution of total area with 1945-analogous climate conditions (combined for all variables), average distance and average direction to these areas is illustrated here for three time slices: (I) 1945, (II) the average European mean annual temperature has increased by 2 °C and (III) the average European mean annual temperature has increased by 4 °C (Fig. 4a–c). An average increase of 2 °C is predicted to occur by approximately 2030–40 for all four scenarios and a change of 4 °C is predicted to occur after 2100 in the B1 scenario and by approximately 2040 in the A1FI scenario.

In the (1945) period, grid cells in eastern Scandinavia, the Alps, the Carpathian Mountains and the hot Mediterranean areas of southern Europe had the fewest analogous areas in the rest of Europe (Fig. 4a, I). By the time mean annual temperature has increased by 2 °C, for most parts of central eastern Europe, Great Britain, Scandinavia and mountainous areas of the Mediterranean there is a decrease in areas with 1945-analogous conditions, whereas in many parts of Italy, southeastern Europe and lowland areas in western and southern regions, 1945-analogous areas will increase (Fig. 4a, II). By the time mean annual temperature has increased by 4 °C, mainly low-altitude areas in southern and eastern Europe will show increased 1945-analogous areas elsewhere in Europe (Fig. 4a, III). All other areas, in particular in central Europe, Great Britain and Scandinavia, are simulated to have fewer or no areas with 1945-analogous conditions. In particular, for northern Scandinavia, central England, the Alps and northern Spain there will be large areas where no 1945-analogous areas can be found anywhere in Europe (black areas in Fig. 4a, III). These large areas with nonanalogous climate conditions at the eastern border of the study area are probably due to an artefact caused by edge effects.

With increased warming, in particular in southwestern and central eastern Europe, the average distance to areas with 1945-analogous climate conditions is predicted to increase, by up to 1000 km (Fig. 4b, II, III). In lowland areas near mountain ranges (e.g. coastal Sweden, northern Italy, northeastern Spain) this distance is often predicted to decrease. Only for some areas, mainly on the Iberian peninsula and to a lesser extent in Scandinavia, is a predicted increase in 1945-analogous areas also accompanied by a decrease in distance to these areas.

There is a trend towards a northeast shift in the average direction to all 1945-analogous grid cells with increased warming (Fig. 4c) for most parts of Europe. During the (1945) period, 1945-analogous cells were located in all directions from cells in central Europe, associated mainly with variation in topography (Fig. 4c, I). With increased warming, the average direction to 1945-analogous cells is predicted to be predominantly northeast (0–60°) with the exception of Italy, Mediterranean areas in southeast Europe and coastal Scandinavia (Fig. 4c, II, III).

DISCUSSION

Total area with and without 1945-analogous conditions

Future climate change will alter the spatial distribution of habitats, biomes and climatically suitable areas (e.g. Saxon et al., 2005). The total area of locations without 1945-analogous climatic conditions elsewhere in Europe is likely to increase by 2100 (Figs 1a and 4) and species endemic to these areas are potentially under threat of not finding suitable climates to migrate to in response to changing climate. On average, any location (grid cell) in Europe is predicted to lose 1945-analogous areas in Europe at a rate of approximately 2600 km² year\(^{-1}\) for the A1FI scenario and 1300 km² year\(^{-1}\) for the B1 scenario by 2100, based on mean annual temperature conditions with a medium tolerance range (Fig. 1b). Loss of all climatically suitable area is likely to lead to habitat and ecosystem loss (Saxon et al., 2005) and the extinction of species. The latter has already been predicted for some European bird and plant species using bioclimatic models (Bakkenes et al., 2002; Thomas et al., 2004; Thuiller et al., 2005). These studies, together with the present analysis, illustrate that for certain species and regions in Europe, loss of climatically suitable areas predicted under future climate scenarios is likely to pose a risk to biodiversity. Areas of northern-central Europe as well as mountainous areas in southern Europe are predicted to be most prone to loss of 1945-analogous areas (Fig. 4a). Lowland areas in south and southeastern Europe on the other hand are likely to experience an increase in area with 1945-analogous conditions.

Distance to areas with 1945-analogous conditions

The risk to biodiversity caused by loss of climatically suitable area may be increased if the remaining areas of suitable climates are also far away (Pitelka et al., 1997). In our study, both average distance to the nearest and average mean distance to all cells with 1945-analogous conditions has increased in the past 50 years and is predicted to increase continuously until 2100 for mean annual temperature (Fig. 2a,b) and for the other four climate variables (Fig. 3). Only for mean annual rainfall is the average distance to all locations with 1945-analogous conditions predicted to remain constant or decrease for some tolerance ranges (Fig. 3b).

Although based on climatic similarity only, these calculated distances might give some indication of migration and dispersal rates necessary to keep up with shifting climates in the future. Climatic zones suitable for forest growth in Europe are predicted to experience a displacement by 150–550 km by 2100 (IPCC, 2001). Applying wide tolerance ranges, our analyses suggest a similar range of increasing average distances to analogous areas for the three temperature-based variables Tm, Tc, and GDD5 (Fig. 3c). Precipitation-based variables (Pa, Pd) are projected to
Figure 4 The spatial distribution of 1945-analogous and 1945-non-analogous conditions for medium tolerance ranges and three periods (I–III): (I) 1945; (II) average European mean annual temperature (Tm) has changed by c. 2 °C (HadCM3, A1FI scenario, 2035); (III) average European Tm has changed by c. 4 °C (HadCM3, B2 scenario, 2095). A cell was considered nonanalogous to 1945-conditions if at least one of the five climate variables was outside the tolerance range (see text for details). Black areas indicate vanishing climates, i.e. areas without 1945-analogous conditions elsewhere in the study area. (a) Total 1945-analogous area (I) and proportional change in 1945-analogous area compared to 1945 (II and III) with green colours indicating an increase and purple colours indicating a decrease in 1945-analogous area; (b) average distance to all 1945-analogous grid cells (I) and change in average distance (II and III) with green colours indicating a decrease and purple colours indicating an increase in distance to areas with 1945-analogous conditions; (c) average direction to all 1945-analogous grid cells. Map projection: Albers equal area.
result in much shorter average distances (< 100 km). This may indicate that, in terms of necessary migration rates, changing precipitation regimes will on average in Europe pose a smaller risk to the biota than changing temperature conditions.

The average minimum distance between the edge of the present distribution and the centroid of the predicted future distribution (2070–99 period, B2 scenario) for 26 European forest herbs was calculated as 211 km by Skov & Svenning (2004) for the same resolution and study area as the present study. For the same scenario and using mean annual temperature alone and a medium tolerance range, we calculated an average distance to the nearest grid cell of c. 142 km. For the A2 scenario, these values were 381 km in Skov & Svenning (2004) and c. 225 km in our analysis. Our values are based only on one variable and are therefore expected to be lower than those of Skov & Svenning (2004). However, they may give some indication of approximate distances; plant species will have to migrate in the future in order to keep up with changing climatic conditions.

Many European trees species generally moved at c. 100 m year\(^{-1}\) since the last glaciation, and few exceeded 1000 m year\(^{-1}\) (Huntley & Webb, 1989; Clark, 1998). Applying mean annual temperature and a wide tolerance range (±2°C) as an example, our study predicts an increase in average distance to all locations with 1945-analogous conditions by 2100 (Fig. 2b). These translate to necessary migration rates of c. 1400 m year\(^{-1}\) (B1 scenario) and 3800 m year\(^{-1}\) (A1FI scenario), higher than the observed migration rates of most European tree species in post-glacial times. This might pose a problem for European tree species with temperature tolerances in terms of reproduction and adult survival) within the above range. However, for species that are able to tolerate temperature changes of more than ±2°C, climatically suitable areas might in future be closer than these distances suggest. Similarly, such distances are unlikely to pose a problem for more mobile species. For example, the most mobile European butterfly species have been reported to have shifted northwards by up to 200 km over a period of only 27 years during the last century (Parmesan et al., 1999; Walther et al., 2002), and mobile forms of one bush cricket species have expanded recently at a rate of c. 7400 m year\(^{-1}\) in England (Simmons & Thomas, 2004).

### Regional climate risk assessment

Using three European regions, the Iberian Peninsula, central continental Europe, and Scandinavia, we illustrate here how different components of climate change can be used to complement regional European risk assessments.

With the exception of some lowland areas, climatic conditions experienced in the Iberian Peninsula in 1945 are expected to decrease in Europe in the future (Fig. 4a). In particular, mountainous areas in central and northern Spain are projected to have no climatically analogous area elsewhere in Europe in the future. This will potentially pose a risk to many species endemic to these areas. At the same time, the remaining areas with 1945-analogous climate will be further away in the future (Fig. 4b) for most northern and southern parts of the Iberian peninsula. Species would have to migrate northeast, crossing the Pyrenees, which could potentially act as a barrier preventing Iberian endemics from extending their ranges elsewhere into southwestern Europe (Fig. 4c). Southern Spain harbours, for example, 14 of Europe’s rarest endemic butterfly species (Kudrna, 2002). The dry areas of southwestern Europe were also identified as high-risk areas by Bakkenes et al. (2002) in their bioclimatic analysis of 1990 European higher plant species.

The climatic conditions experienced in central continental Europe in 1945 are predicted to be much reduced in area and a long way away, in the future (Fig. 4a, b). Both of these risk components could potentially pose a threat to European mammals, for which species richness is highest in central Europe (Mitchell-Jones et al., 1999). In the future, 1945 conditions will be found mainly to the north-east (Fig. 4c), in Scandinavia. This might indicate further increased risk, as species will have to migrate east through potentially less suitable climatic conditions in order to circumvent the North and Baltic Seas, and also have to negotiate heavily cultivated areas of the north-European plain. This northeastern trend is partly determined by European geography (e.g. the cold Scandinavian mountains are to the NE of most of Europe, but to the NW of the eastern European lowlands), and partly by artificial edge effects due to the eastern truncation of the study region, in the analysis. However, it is likely that many species will have to move north or north-east in order to find suitable climate in the future, as shown for example for trees by Skov & Svenning (2004). Mountains may act as barriers and therefore pose a risk (e.g. the Pyrenees for species on the Iberian Peninsula), or they may act as refugia (e.g. the Alps for species in the northern Italian lowlands).

The conditions found in large parts of northern Scandinavia in 1945 will no longer be found anywhere else in Europe by the time the mean annual temperature in Europe has increased by 4°C (black areas in Fig. 4). This could potentially pose a high risk for species restricted to these areas in Europe, such as the Arctic fox (Alopex lagopus) and the Norway lemming (Lemmus lemmus) (Mitchell-Jones et al., 1999). Norway and Sweden list 255 (http://www.environment.no; accessed 5 April 2005) and 505 (http://www.planntalk.org/country/sweden.html; accessed 5 April 2005) threatened plant species, respectively, which are potentially under threat of loss of areas with suitable climate. Biodiversity in Arctic and boreal regions has already been identified as suffering the most from climate change compared to other biomes (Sala et al., 2000). The only positive note is that when suitable conditions do persist in Scandinavia, those locations will, for some southern and coastal areas, not necessarily be far away (Fig. 4a, b).

The decrease in area of 1945-analogous conditions and the decrease in distance to these areas in Scandinavia is likely to be, at least to some extent, an artefact of the artificially truncated eastern boundary of our study area. As Malcolm et al. (2002) have shown, climate is expected to change most rapidly in the extensive northern boreal areas, and species and biomes may have to move long distances. The conditions that were present in ‘non-analogous’ locations in Scandinavia (Fig. 4a, III) may still be found in the future, but well to the east of our study area. We used the HadCM3 climate model for our analyses. However, it should be
kept in mind that the spatial distribution of analogous and non-analogous conditions in the future is likely to be different for different climate models.

CONCLUSIONS

We present a species-independent analysis of climate change risk at the European level which illustrates that the loss of climatically suitable area and the distance to areas with suitable climate in the future are likely to vary among regions. Simply by superimposing the current distributions of species and habitats on these surfaces can provide a preliminary impression of the potential threats: European regional risk assessment based on species distribution models and extinction rates can be complemented by the climate-only risk assessment presented here. Different climate models predict different spatial distributions of future climatic conditions and the models used here cover most, but not all, of the possible distributions of future climate space. However, our analysis illustrates how different aspects of climate change-induced risk vary in magnitude across Europe, with the complete loss of suitable conditions being the main problem in some regions, and long migration distances being the main problem in other regions. Extending simple calculations of change in climatically suitable area under future climate scenarios through the incorporation of direction and distance to climatically suitable areas can add valuable information to regional climate change risk assessment.

ACKNOWLEDGEMENTS

This work was funded by the EU FP6 project ALARM (‘Assessing large-scale environmental risks for biodiversity with tested methods’), contract no. GOCE-CT-2003–506675. Markus Erhard, from the EU FP5 project ATEAM, kindly provided the climate surfaces. Two anonymous referees made very valuable suggestions which improved the quality of our analyses.

REFERENCES


**BIOSKETCHES**

**Ralf Ohlemüller** is a postdoc with the EU FP6 project ALARM and is interested in patterns of species distributions in fragmented landscapes and processes determining community structure at various scales.

**Emmanuel Gritti** is a doctoral student and is working on vegetation modelling and vulnerability of Mediterranean Island ecosystems to alien plants invasion under climate and disturbance changes during the coming century.

**Martin Sykes** is a professor of plant ecology and leads the ‘Ecosystem Modelling and Biodiversity Studies Group’ at Lund University, which is involved in a number of Swedish and EU FP5 and FP6 projects dealing with modelling the responses of vegetation and ecosystems to climate.

**Chris Thomas** is a professor of conservation biology and works on the combined impacts of landscape pattern and climate change on the distributions, ecology and evolutionary biology of plants and animals, particularly butterflies.

Editor: Wolfgang Cramer