Fig. 4.1 Alternative responses to climate change.
The rectangular area represents an arbitrary geographical space within which the ellipses represent either the geographic range of a species or the area of intersection between geographical space and climate space within which the species' initial climatic requirements/tolerances are met. An initial situation (A) is shown in which the species is in equilibrium with climate so that its area of occurrence coincides with the area within which its present climatic requirements/tolerances are met (green ellipse). The other three diagrams represent alternative situations following a major climate change such that the area within which the species' initial climatic requirements/tolerances are met no longer overlaps the species' initial range but instead is represented by the additional ellipse in the upper right-hand corner of the geographic space.

In the first of these (B) the species has responded to the climatic change spatially, by migrating so as to maintain its range in equilibrium with the changing climate; its new range thus coincides with the area within which its initial climatic requirements/tolerances are now met (green ellipse) and it is no longer present in its initial range (empty ellipse). The second case (C) represents an evolutionary response; the species has evolved new climatic requirements/tolerances enabling it to sustain its original geographic range (lavender ellipse), which no longer overlaps the area within which its initial climatic requirements/tolerances are now met (yellow ellipse). The third case (D) represents failure to exhibit a spatial or an evolutionary response; the area within which the species' initial climatic requirements/tolerances are now met (yellow ellipse) no longer overlaps its original geographical range (empty ellipse), within which it is now extinct.

Fig. 4.2 Combined spatial and evolutionary response to climate change.
As in Fig. 4.1, the rectangular area represents an arbitrary geographical space. The shaded ellipses represent the geographical range of a species that is in equilibrium with climate and thus is occupying the area of intersection between geographical space and climate space within which its climate requirements/tolerances are met. The empty ellipses represent the species' range before/after a climate change, reflecting the element of spatial response indicated by the unshaded arrow in B. The varying shades, from purple to green, within the ellipses representing the species' occupied geographical range indicate the varying genotype of the species, which exhibits climatically related clinal variation within its area of occurrence.

In the first case (A) the species' range is in the 'south-west' of the geographical area and 'purple' genotypes are predominant. In contrast, following the climatic change (B) the species' geographical range is 'north-eastern' and 'green' genotypes predominate. Note that the more extreme 'purple' genotypes are absent in B and the more extreme 'green' genotypes absent in A; this reflects a shift in the position in climate space, as well as in geographical space, of the intersection between the two within which the species' climatic requirements/tolerances are met. The species' response to this changed intersection has been evolutionary and is indicated by the shaded arrow in B. Note also that the genotype of individuals within the geographical area occupied both before and after the climatic change has also changed, being toward the 'green' end of the range in A, but being replaced by genotypes more toward the 'purple' end of the range in B.

Fig. 4.3 Individualistic responses of two species to a climate change.
As in the previous figures the rectangles represent an arbitrary geographical space and the shaded ellipses represent the geographical ranges of two species that are in equilibrium with climate and thus are occupying the area of intersection between geographical space and climate space within which their climatic requirements/tolerances are met. The shading within the ellipses reflects the genotypes of the species, each species exhibiting clinal variation in relation to climate. The empty ellipses in each case represent the geographical range of the other species. The geographical distributions of the first species are shown in A and B whereas those of the second are shown in A′ and B′. In the initial situation (A and A′) the two species exhibit overlapping distributions although their

climatically determined clinal variation patterns are orthogonal to one another. Following climate change (B and B′) each species exhibits a combination of spatial and evolutionary responses as a consequence of which their geographical ranges no longer overlap. This reflects the failure of the climate conditions jointly favourable both to the more 'blue' genotypes of the first species and to the more 'red' genotypes of the second any longer to intersect the geographical space. Instead, the more extreme 'green' genotypes of the first and 'blue' genotypes of the second, which occupy distinct climatic conditions, are now favoured in different parts of the geographical space.

Fig. 4.4 Alternative mechanisms of extinction as a consequence of climate change.
Three alternative extinction mechanisms are illustrated by the sequence of panels. Time advances from the top panel downwards, as indicated by the arrow. As time advances, the climate of the geographical area represented by the rectangle changes progressively. This climate change impacts upon the location and/or extent of the geographical area within which each species' climatic requirements/tolerances are met. These areas are represented by the ellipses, which are shaded if the species is occupying them and empty with a dashed outline if the species is absent.

Species A (green) experiences a progressive and severe reduction in its potential range from time *t* to time *t*+3 followed by an increase at times *t*+4 and *t*+5. The extreme reduction of its range at time *t*+3, however, renders it extremely susceptible to stochastic extinction as a consequence of extreme environmental events or random population fluctuations; thus it has become extinct before the subsequent increase in its potential range at time *t*+4.

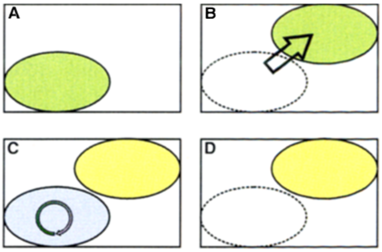
Species B (red) experiences progressive but less severe range reduction from time *t* to time *t*+3. However, at time *t*+3, a second discrete area of potential range becomes available in a different part of the overall geographical space. By time *t*+4 the original component of the potential range has disappeared; the new component, however, has increased in extent and does so again at time *t*+5. The species nonetheless becomes extinct because it is unable to achieve the long-distance dispersal necessary to cross the spatial discontinuity between the two component parts of its potential range at time *t*+3.

Species C (blue) experiences a progressive but moderate range reduction from time *t* to time *t*+3. At time *t*+2, however, no part of the geographical space offers climatic conditions that satisfy its requirements/tolerances and it thus has no potential range. Although suitable conditions are once again available at time *t*+4 and the area of its potential range increases once again thereafter, it has become extinct at time *t*+3 as a consequence of the temporal discontinuity in its potential range.

Fig. 4.5 Schematic representation of the consequences of a rapid climate change.
Once again the rectangle represents a geographical space, the four panels representing successive situations along a time-series that advances downwards, as indicated by the arrow. The ellipses again represent the range of a species that initially, at time *t*, is occupying fully its potential climatically determined range, as indicated by the shading of the entire ellipse.

Climate changes progressively at times *t*+1 to *t*+3 so that the species' potential range steadily shifts north-eastwards; this potential range is indicated by the ellipse with the dashed outline. The species migrates north-eastwards in response to this climate change, which makes new areas of potential range available along the north-eastern sector of its previously occupied range. However, the species' migration rate is insufficient to maintain its advancing range margin in equilibrium with climate. At the same time, climatic conditions in parts of its original range no longer satisfy requirements/tolerances and consequently it dies out in those areas. The overall consequence is a reduction in the area occupied by the species, as indicated by the shaded area at each time step, so that by time *t*+3 it has suffered a severe reduction in range and hence also in population. Even if no further climate change occurred after time *t*+4, the species has been rendered vulnerable to extinction because its population has been severely reduced. If climate change continued at the same rate for one more time step then the species would become extinct as a result of its failure to migrate at a sufficient rate to continue to occupy any part of its potential range.

Fig. 4.1



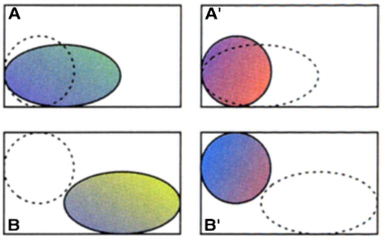


Fig. 4.3

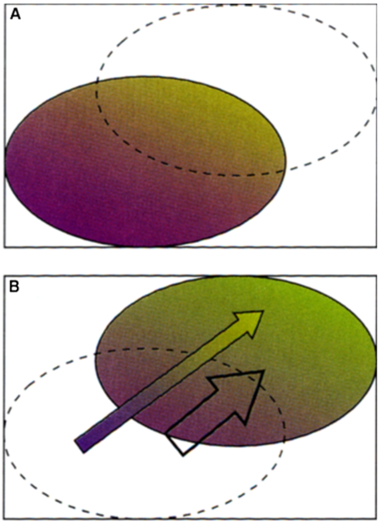


Fig. 4.2

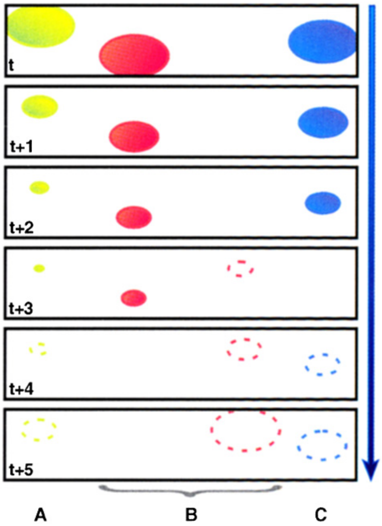


Fig. 4.4

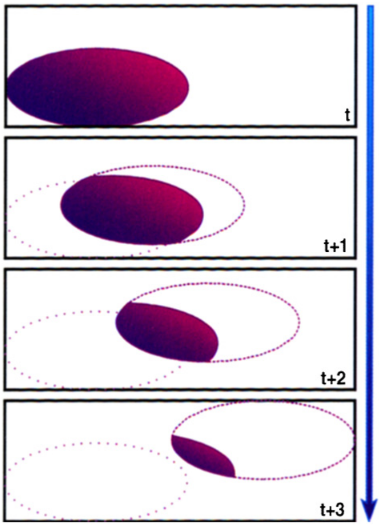


Fig. 4.5

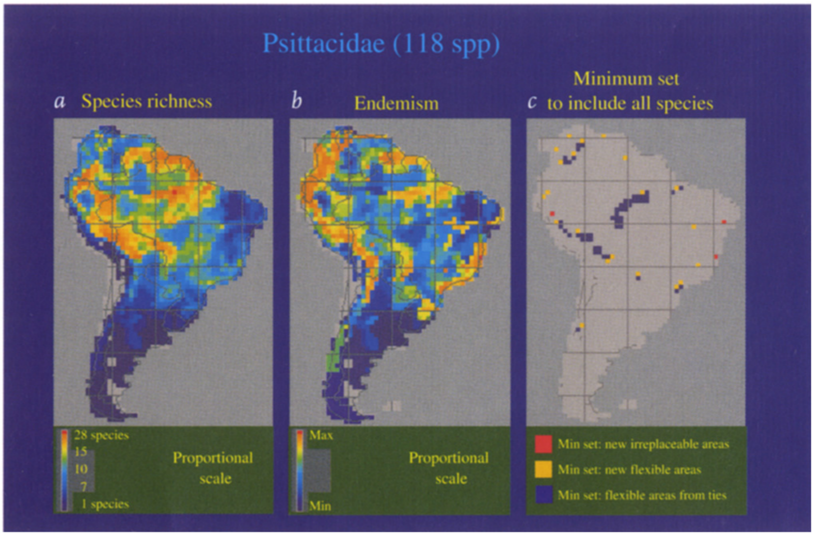


Fig. 7.1 The variation in species richness (*a*) and endemism (*b*) for 118 species of parrots, Psittacidae, with the near-minimum set of irreplaceable and flexible areas needed to cover all species (*c*).

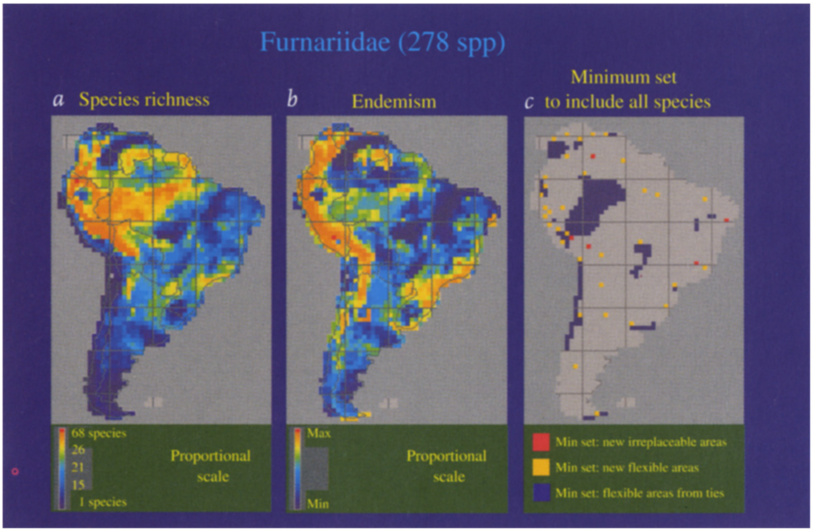


Fig. 7.2 The variation in species richness (*a*) and endemism (*b*) for 274 ovenbirds and woodcreepers, Furnaridae, with the near-minimum set of irreplaceable and flexible areas needed to cover all species (*c*).

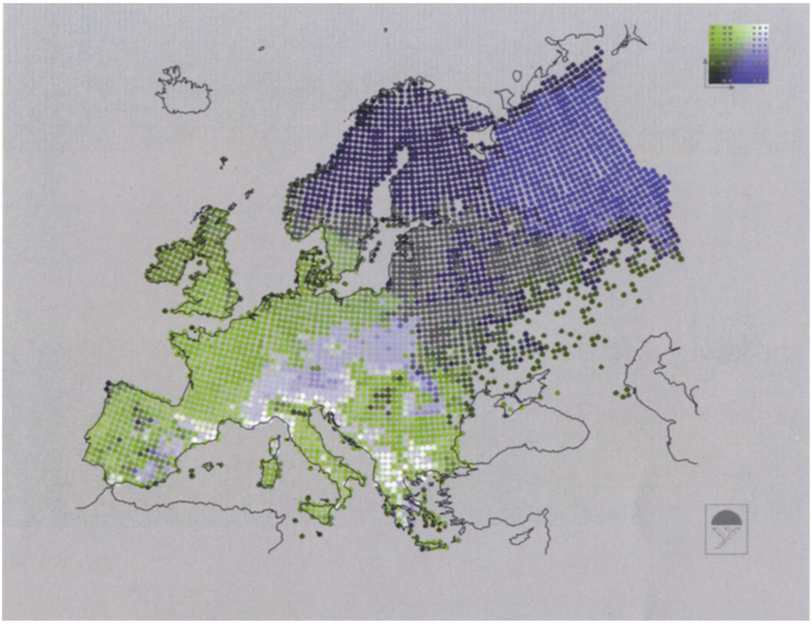


Fig. 10.2 The geographical pattern of deviations from any 'indicator' relationship of diversity between two groups of organisms can be visualized by overlaying the two diversity maps in two separate colours (Williams 1996a). Here, increasing intensity of blue is used to represent increasing species and subspecies richness of Pinaceae (pines, first, spruces, larches) and increasing intensity of green is used for increasing species and subspecies richness of Fagaceae (oaks, beeches and chestnut). Consequently, black grid cells on the map show low richness for both; white shows high richness for both; and shades of grey show intermediate and linearly covarying richness for both (these covarying scores lie on the diagonal of the colour key, to the upper right of the map). In contrast, areas of the map with highly saturated blue cells show an excess of richness for Pinaceae over Fagaceae, and areas with highly saturated green show an excess of Fagaceae over Pinaceae (Spearman correlation coefficient $rho = -0.33$, $P < 0.0005$). The colour classes are arranged to give even frequency distributions of richness scores along both axes (at least within the constraints imposed by tied richness scores), between the observed maximum and minimum (non-zero) scores. For a review of similar colour systems see Brewer (1994), and for an example of a three-dimensional plot see Williams (1993a). Data are taken from joint work with Chris Humphries, Raino Lampinen, Tapani Lahti and Pertti Uotila, for 'native' records for 50 × 50 km grid cells from the *Atlas Florae Europaeae*.

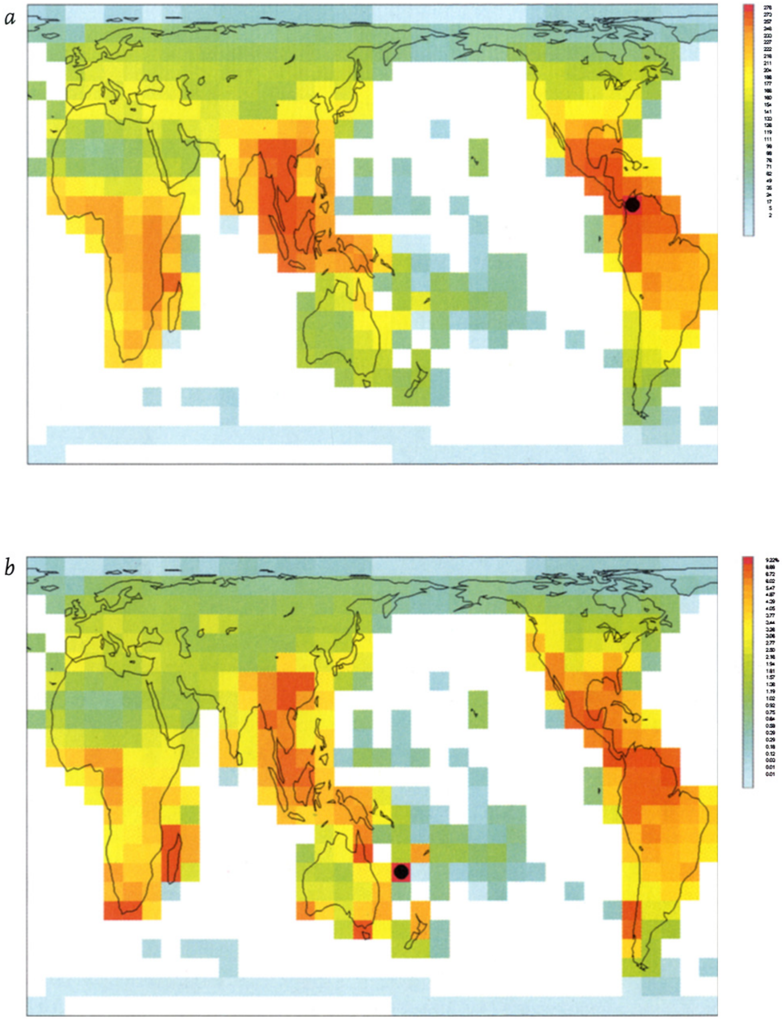


Fig. 10.3 Maps combining (*a*) family richness and (*b*) family range-size rarity (showing concentrations of narrow endemism) of terrestrial and freshwater seed plants, amphibians, reptiles and mammals world-wide on an equal-area grid map (grid-cell area *c.* 611 000 km^2, for intervals of 10° longitude). Range-size rarity is measured by summing the inverse of the range sizes for each family in a grid cell. Maximum scores are shown in red with a white spot, other scores are divided into 32 colour-scale classes of approximately equal size by numbers of grid cells. Although the numerical values differ, the frequency classes (with nearly equal areas) remain comparable among maps. After Willams, Gaston & Humphries (1997).