Egypt's Protected Area network under future climate change

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A B S T R A C T

Concerns about the impacts of climate change loom large among biodiversity scientists. A pressing issue is the role of Protected Area networks under future climate change, because of the shifting of species distributions polewards due to climate warming. In this study we use two techniques in conservation science, first, to estimate the likely impacts on the distributions of mammals and butterflies in Egypt (MaxEnt), and second, to measure the effectiveness of Egypt's Protected Area network (Zonation). We predict that future climate will have significant effects on species richness and the relative value for conservation of sites in Egypt: some areas will increase in species richness, whilst others will decrease significantly. Currently, the sites of highest relative conservation value are found in the Nile Delta, southeastern and Sinai regions of Egypt and along the Mediterranean and Red Sea coastlines, with Protected Areas having a higher conservation value than unprotected areas. Under future climate scenarios the relative conservation value of Protected Areas are predicted initially to decline and then gradually increase by the 2080s. It is predicted that many areas, especially the Nile Delta and the southeast, will require extra protection in the future; areas that are currently not protected, but have high species richness and conservation value, may need to be protected to prevent loss of biodiversity.

1. Introduction

Recent climate warming is thought to be affecting greatly the distribution of species globally (Parmesan and Yohe, 2003; Dawson et al., 2011), causing great concern to conservation biologists because of the effects on biodiversity (Brooks et al., 2006). Species distributions may change even more dramatically under future climate change scenarios, as many physiological and ecological processes will be affected (Hansen et al., 2006). One of the impacts of global climate change is to alter the effectiveness of Protected Areas, i.e. how well they can support species in the future. A new framework for conservation, that accounts for species distribution shifts in response to climate change, is required to be able to adapt and allocate financial resources efficiently (Hannah, 2010).

Species could adapt their niche and hence remain where they are, or they could move, maintaining their niche (Wiens et al., 2010): the main biological signals of climate warming reported in the literature have been phenological changes and polewards shifts in distribution (Parmesan, 2006; Root et al., 2003). Lack of connected habitat patches, exacerbated by human habitat destruction, prevents some species from moving (Honnay et al., 2002). Distributional shifts of some species will certainly change the distribution of biodiversity (Menendez et al., 2007) and cause a decline in species richness of particular places (Hannah, 2008), including reserves as some species shift to non-reserve areas (Araujo et al., 2004). These losses may be partially offset as new species invade from habitats outside Protected Areas (Hartley and Jones, 2003). Therefore it is unclear whether Protected Areas will lose species or not under future climate warming (Hole et al., 2009; Araujo et al., 2011), but those that encompass greater latitudinal and altitudinal variation may be better able to retain species under future climate warming (Hannah, 2008).

The global network of Protected Areas has continued to grow steadily since 1992, increasing by an average of 2.5% in total area per year (Butchart et al., 2010). Currently Protected Areas occupy almost 17 million km^2 worldwide (~19% of global land area), but only ~5.8% is strictly protected for biodiversity (Jenkins and Joppa, 2009). Global estimates suggest that Protected Areas do not overlap the most biodiverse areas (Chape et al., 2005) and climate change could compromise their ability to do this even more (Carroll, 2010). It is important, therefore, to be able to assess the likely effectiveness of a Protected Area network under future scenarios of climate change.

A fairly recent technique devised for just this purpose uses a combination of species distribution modelling and reserve-selection algorithms such as Zonation (Hannah, 2008, 2010; Carroll, 2010; Klorvuttimontara et al., 2011). This combination allows for the analysis of large data sets in a reasonable time and may provide

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the best solution for assessing the conservation value of Protected Area networks. Species distribution modelling is one of many methods used to quantify patterns of species distributions and to extrapolate distributions across space and time (Elith and Leathwick, 2007; Franklin, 2009), usually based on a statistical model (Franklin, 2009). This is done by combining species occurrences at known locations with layers of environmental variables thought to have an influence on habitat suitability (and so species distribution) to make a model of the environmental conditions that meet the ecological requirements of a species, thus identifying where these suitable conditions are distributed in space (Guisan and Thuiller, 2005; Phillips et al., 2006; Pearson, 2007; Elith & Leathwick, 2009; Franklin, 2009; Warren and Seifert, 2011). The output of most models aims to provide detailed predicted distribution maps (Elith et al., 2006). Once built, such models can be used to supply projections of potential habitat, which can be used as a surrogate for biodiversity maps, and in areas with poor species data they can predict the distribution of species under different environmental conditions (for example, future climate change) and inform conservation management (Wintle et al., 2005). Species distribution models assume that distributions are caused by environmental tolerances, i.e. the Grinellian or fundamental niche. The responses of species to these niches are then estimated, assuming these will not change under future climate: species will move rather than adapt (Wiens et al., 2010). It has the potential to include species interactions (Kissling et al., 2011), but these are hard to incorporate into an analysis of an entire fauna without solid a priori bases for including particular interactions for each species (McMahon et al., 2011). There are a range of methods available, but here we used MaxEnt (Phillips et al., 2006), based on the probability distribution of maximum entropy, subject to environmental variables (Elith et al., 2006, 2011).

Spatial conservation prioritisation techniques use spatial data, such as species distribution and land cover, to analyse and prioritise areas that require conservation (Kremen et al., 2008). 'Zonation' is an implementation of spatial conservation prioritisation able to examine the effectiveness of Protected Areas (Moilanen et al., 2005). Recent studies have used it to prioritise areas for conservation in many different countries: to increase the reserve network for lemurs in Madagascar (Kremen et al., 2008; Fiorella et al., 2010), in the design of marine (Leathwick et al., 2008) and riverine Protected Areas (Leathwick et al., 2008, 2010) and for forest conservation in Finland (Lehtomaki et al., 2009) and the USA (Carroll, 2010).

We apply these techniques here to Egypt, which has 29 Protected Areas covering 15% of its land surface (EEAA, 2010), and one more small one recently declared on the southern border with Sudan. All of these have been gazetted since 1983, and show very good coverage of biodiversity compared to Protected Area networks in other countries (Newbold et al., 2009). The effect of climate change on species distributions in Egypt has never been studied, and neither has the efficiency of the Protected Area network to conserve biodiversity in the advent of climate change. The datasets for Egyptian mammal and butterfly species are large and complete enough, so both of these taxa were chosen to be used in our models. Egyptian mammal and butterfly species have higher species richness inside the network than outside, and at present the network seems to contain a fair representation of Egypt's mammal and butterfly diversity (Newbold et al., 2009). We address whether future climate change may affect the ability of the network to represent biodiversity successfully.

2. Materials and methods

2.1. Species and climate data

We took advantage of the fact that occurrence data for many taxa from Egypt have been collated, taxonomically checked and updated, assessed and georeferenced as part of the BioMAP project (2004–2008), which aimed to develop and strengthen biodiversity research across Egypt (see http://www.biomapegypt.org). The mammal dataset consists of 4533 verified records for 60 species, taken from museum and personal records, unpublished reports and the published literature (Basuony et al., 2010), nearly all recorded between 1900 and 2007: coverage is good (Appendix – Document 1 – Fig. A1) considering that most of Egypt is arid inaccessible desert. The butterfly dataset contains 1729 records, nearly all recorded between 1900 and 2006, for 36 species, mostly taken from museum specimens and the sparse literature on Egyptian butterflies (Larsen, 1990; Gilbert and Zalat, 2008). The coverage of Egypt is patchy (as might be expected for butterflies in the most arid country in the world), but fairly representative (Appendix – Document 1 – Fig. A1). All specimens in Egyptian collections were re-identified according to the latest taxonomic opinion; Larsen (1990) had already reviewed and checked most other records. The precision of the locality information was assessed and records rejected that were too imprecise to be mapped. Given that nearly all the records were collected before the era of GPS units, and that Egyptian data are not so numerous, we could not afford to be too highly selective; we accepted all mappable records as potentially usable where the majority were post-1900 (see below). There is bias in the data in that records were inevitably made in accessible rather than inaccessible locations, a notable problem in a country such as Egypt, where for most of the 20th century roads were largely limited to the Nile Valley and Delta, and the northern coast. As for most countries in the world, we were unable to assess or allow for such biases in the analyses: they probably do affect interpretation of the static pattern (cf. Basuony et al., 2010) but changes with time should be less affected.

Although desirable, we were unable to include the possibility that species from outside Egypt might invade under climate change scenarios, simply because the distribution data do not exist for surrounding countries, particularly Sudan to the south, from where such species might reasonably derive. This limits the interpretation of our results to the current species recorded from Egypt.

Egypt is the most arid country in the world (FAO, 2012), with mean annual rainfall in most of the southern regions of less than 2 mm per year, reaching 100–200 mm per year on a narrow strip of the Mediterranean coast and in the Sinai mountains. Mean annual maximum temperatures range from 20 to 35 °C, with the average maximum July temperatures in the south approaching 50 °C. Mean annual minimum temperatures range from 10 to 19 °C, with average minimum January temperatures between zero and 5 °C in the Sinai mountains (EMA, 1996).

Current monthly climate data at 2.5 arc-min resolution (pixel size is approximately a square of side 4.6 km) describing precipitation and temperature were obtained from the WorldClim version 1.4 dataset (Hijmans et al., 2005), derived from observed data collected in the period 1950–2000. Current and future climate data were downloaded in the form: tmin (average monthly minimum temperature (°C)), tmax (average monthly maximum temperature (°C)) and prec (average monthly precipitation (mm)). Future downscaled climate data for the same variables, based on the IPCC Fourth Assessment Report, were obtained from the CIAT (International Centre for Tropical Agriculture) website (http://gisweb.ciat.cgiar.org/GCMPage), again at 2.5 arc-min resolution. Climate data was downloaded from three different climate models: HadCM3 (developed by the UK Met Office Hadley Centre), CSIRO MK2 (developed by the Australian CSIRO Climate Change Research Programme) and NIES99 (developed by the Japanese National Institute for Environmental Studies). The data were for three future time periods (2020s, 2050s and 2080s) and for two emission scenarios (A2 and B2) chosen because they represent 'moderate' (B2) and 'large' (A2) changes, and are thought to account for most of the

likely variation in future greenhouse gas emissions (Beaumont et al., 2008). The current and future climate data were then clipped to the outline of Egypt using the Raster Calculator function in Arc-Map 10.0 (ESRI, Inc.), and converted to a standard set of climate predictors: the mean, maximum, minimum and standard deviation were calculated for *tmin* and *tmax*, and the sum, maximum, minimum and standard deviation were also calculated for *prec*. This process created 12 new variables which were used as climate predictors: *max tmin*, *max tmax*, *max prec*, *min tmin*, *min tmax*, *min prec*, *std tmin*, *std tmax*, *std prec*, *sum prec*, *mean tmin*, and *mean tmax*.

2.2. Modelling species distributions in the current and future climate

Some authors (e.g. Araujo and New, 2007; Thuiller et al., 2009) advocate using ensemble modelling for species distributions, where the consensus view over a number of kinds of model is used in order to incorporate modelling uncertainty. We did not use this methodology because (a) we wanted to keep things as simple as possible – the nature of the data is the main limiting issue in data-poor countries such as Egypt; and (b) different models have differing data requirements and hence ensemble modelling would necessitate rejecting many more species than MaxEnt. We therefore used a single modelling method (MaxEnt: see Elith et al., 2006, 2011) to keep the model type constant over all models. MaxEnt is a robust and useful method, used extensively by researchers in this field, although there are dissenters who believe it to be inappropriate for a variety of reasons (e.g. Royle et al., 2012).

Our models assume that climate is the determinant of the distribution of the species. This is simplistic, but practical (McMahon et al., 2011): the extent to which distributions are determined by other factors, such as species interactions and abiotic factors (for example land use or vegetation), is simply unknown. It might have been feasible to search for such relationships among the data, but in our opinion this was more likely to generate spurious than real relationships. Almost nothing is known *a priori* about factors such as interactions among Egyptian mammals. Although host-plants are known for some Egyptian butterflies, we do not yet have the data on plant distributions to be able to incorporate them as possible predictors. MaxEnt models for 10 Egyptian butterfly and 4 Egyptian mammal species (all used in this study) have been validated by collecting new information from the field in small surveys (Newbold et al., 2010).

Using MaxEnt (version 3.3.3), species distribution models were built with the climate variables for Egyptian mammal and butterfly species, checked and validated elsewhere (Newbold et al., 2009, 2010). Only species with at least fifteen records of occurrence and from precise locations were included in the modelling as this is widely recommended as the best number to use (Papes and Gaubert, 2007; Pearson et al., 2006). MaxEnt is designed for use with datasets that contain presence-only data, and is therefore one of the best techniques to use when a large majority of the data comes from museum collections (Elith et al., 2006), as is the case in this study. It is also known to be especially useful with low numbers of records (Elith et al., 2011), as with many of the rarer species here: we used all available records for building each model. It is certainly possible that the relatively low number of records for many species affects the results, but averaging over many species should mitigate the impact. In addition, species with more than 50% of their records dated before 1900 were excluded from the models (see Appendix – Document 1 – Table A1). The years of all mammal and butterfly species records can be found in Appendix – Document 2 – Table A5 and Appendix – Document 3 – Table A6 respectively. Models were assessed using the usual AUC criterion and any species with an AUC score lower than 0.7 were excluded from future models (see Appendix – Document 1

– Table A1). A score greater than 0.7 is thought by most researchers in this field to represent an accurate model (Swets, 1988; Fielding and Bell, 1997). The robustness of the models was also tested using Kappa analysis in R (version 2.15.1), performed for the 60 mammal and 35 butterfly species used in the analysis (see Appendix – Document 1 – Table A1).

In total 60 terrestrial mammal (65% of the fauna) and 35 butterfly (56%) species were modelled. The following parameters were used in MaxEnt: linear and quadratic feature types; maximum of 500 iterations; response curves; jackknife; and a 25% random test percentage was used to determine background predictions for Kappa values. MaxEnt predictions for current species' distributions are shown in Appendix – Document 4 – Table A7.

2.3. Spatial conservation prioritisation in current and future climate

The priority areas for conservation were identified using Zonation software (Moilanen et al., 2005, 2009), which prioritises by considering the landscape as a grid of cells. It repetitively removes cells whose loss causes the least marginal loss in the overall 'conservation value' (see below) of the remaining landscape, resulting in a rank order for all cells. The top-ranking cells after these processes indicate areas of highest priority for conservation (Moilanen et al., 2005).

The predicted distributions from MaxEnt in the form of raw values for each pixel, for 60 mammal species and 35 butterfly species were used by Zonation (version 2.00) to prioritise areas for conservation under current and future climates. There are four elements of Zonation that require choices to be made, and we performed four different runs using different assumptions (Table 1) for two of the elements: the weighting of species and the cell removal rule (which determines what 'conservation value' means). The other two (the 'warp factor' and the connectivity of the habitat) were chosen to be constant among runs.

When assigning weights to each individual species, we used two equations: weight = distribution² × IUCN (for runs 1 and 3) and weight = distribution × IUCN (for runs 2 and 4). In these equations, 'distribution' is a score (between 1 and 5) derived from an estimate of the degree to which Egypt is responsible for the world population (see Table 2), and 'IUCN' is a codified version of the Red List categories (see Table 2) (scored between 0 and 5). The resulting weights for each species are given in Appendix 1 – Document 1 – Table A2.

The cell removal rule (see Moilanen, 2007) determines how the algorithm assesses 'conservation value' in order to rank the cells of the landscape. We firstly used 'Core-Area Zonation' (runs 1 and 2), where the conservation value of a cell is defined as the highest value for any one species of the equation Qw/c, where w is the species weight, Q is the proportion of remaining distribution of the species that the cell represents (based on probabilities of occurrence from MaxEnt), and c is the cost of adding the cell to the reserve network (a cost value was not used in this study). We then replaced this with the 'Additive Benefit Function' (runs 3 and 4), which defines conservation value as the sum of the values of the cell over all

Table 1
Settings used in different runs of Zonation. Four elements have options, and we changed two of them among different runs (see text). The 'aggregation method' (chosen to be 'distribution smoothing') and the 'warp factor' (chosen to be 100) were constant among runs: see text.

Run	Cell removal rule	Weighting of species
Run 1	Core area Zonation	Distribution² × IUCN
Run 2	Core area Zonation	Distribution × IUCN
Run 3	Additive Benefit Function	Distribution² × IUCN
Run 4	Additive Benefit Function	Distribution × IUCN

Table 2
Coding for 'distribution' and 'IUCN' used in calculating the species weights for different runs of Zonation (see methods). The categories were obtained for each species from Basuony et al. (2010) (mammals) and Gilbert and Zalat (2008) (butterflies). The resulting scores are provided in Appendix – Document 1 – Table A2.

Distribution	Score	IUCN category	Score
		Not assessed	0
Widespread	1	Least concern	1
Narrow	2	Data deficient	2
Restricted	3	Vulnerable	3
Near-endemic	4	Endangered	4
Endemic	5	Critically endangered	5

species, thus giving more weight to areas of high species richness. In this study species richness refers to the sum of the probabilities of occurrence. The input parameter of the Additive Benefit Function determines the rate of loss of conservation value as area is removed: we used a value of 0.25 for all species, because this value is approximately the exponent of species–area relationships (Ferrier et al., 2004).

Two elements were constant among runs. The warp factor is the number of grid cells removed in each iteration; in this study we set it to 100 as the best compromise between speed of run and reproducibility of results. The other element constant among runs was the connectivity of the habitat, set by choosing an aggregation method. There are four types of aggregation method: 'boundary length penalty', 'distribution smoothing', 'boundary quality penalty' and 'directed connectivity'. Which is appropriate depends on the conservation target and computational issues, but their use provides a relatively compact solution (Moilanen and Kujala, 2006). In this study we used distribution smoothing, which necessitates the calculation of a parameter α by the following equation: $\alpha = (2 * [\text{cell size in km}^2])/([\text{dispersal distance in km}] * [\text{input cell size in km}])$. The input cell size was set as 0.0416 km ($\equiv$0.0083°), and the cell size to 4.6383 km ($\equiv$2.5 arc-min resolution). The last part of the equation (cell size (km^2)/input cell size (km)) is needed to ensure that the α value is in the same unit of length as the cell size given in the species distribution ASCII file (Moilanen and Kujala, 2006). The dispersal distance was calculated differently for mammals and butterflies. Butterflies were classified either as resident and/or migratory (Appendix – Document 1 – Table A2) (Gilbert and Zalat, 2008), so the dispersal distance was estimated as dichotomous: 1 km for residents and 50 km for migratory species. For mammals, an equation links dispersal distance to body size, Log_{10} (dispersal distance in km) $= -1 + (0.62 \times \text{Log}_{10}$ (body size in g)) (Bowman et al., 2002), and then the corresponding α values were calculated. The parameters used in calculating α for each species are given in Appendix – Document 1 – Table A3.

2.4. Interpretation and processing

Species Richness maps were created by summing all of the output ASCII files for both mammals and butterflies. We did not convert the MaxEnt raw output into 'presence–absence' using a threshold rule, because (a) this involves an extra set of assumptions we did not want to make; and (b) an as-yet-unpublished parallel study of reptile diversity and climate change (El-Gabbas, 2012) showed no difference in the results of such a conversion.

To examine the conservation value of Protected Area networks under current and future climate, grid cells were prioritised using current and future distributions of mammals and butterflies. Zonation ranks each cell from 0 (low) to 1 (high), and in this study we designated cells with a score >0.7 as 'high priority', in order to observe what proportion of these high-priority grid cells are protected at any single time period. For each Zonation run and climate model, we calculated the mean ranked score of cells and

number of high ranked cells contained within the current Protected Area network under current and future climate change scenarios. Egypt covers approximately 48,000 grid cells at 2.5 arc-min resolution, of which about 8.0% are within the 27 Protected Areas considered here (Appendix – Document 1 – Table A4): the newest Protected Areas (El Gilf El Kebir, El Dababia and Gebel Kamel) were not included in this analysis because they are little more than paper parks at the moment. For each scenario (A2 and B2), the results were then averaged across the three Global Circulation Models and across all four runs of Zonation to produce mean ranked scores and number of high-value grid cells within and outside PAs. We averaged the results across all Global Circulation Models because there were no major differences between individual models – the projections all resulted in approximately the same patterns. The output maps from Zonation were also averaged per cell across all three Global Circulation Models and all four runs of Zonation to produce maps showing the 'relative conservation value' of grid cells in Egypt for mammals and butterflies under current and future climate.
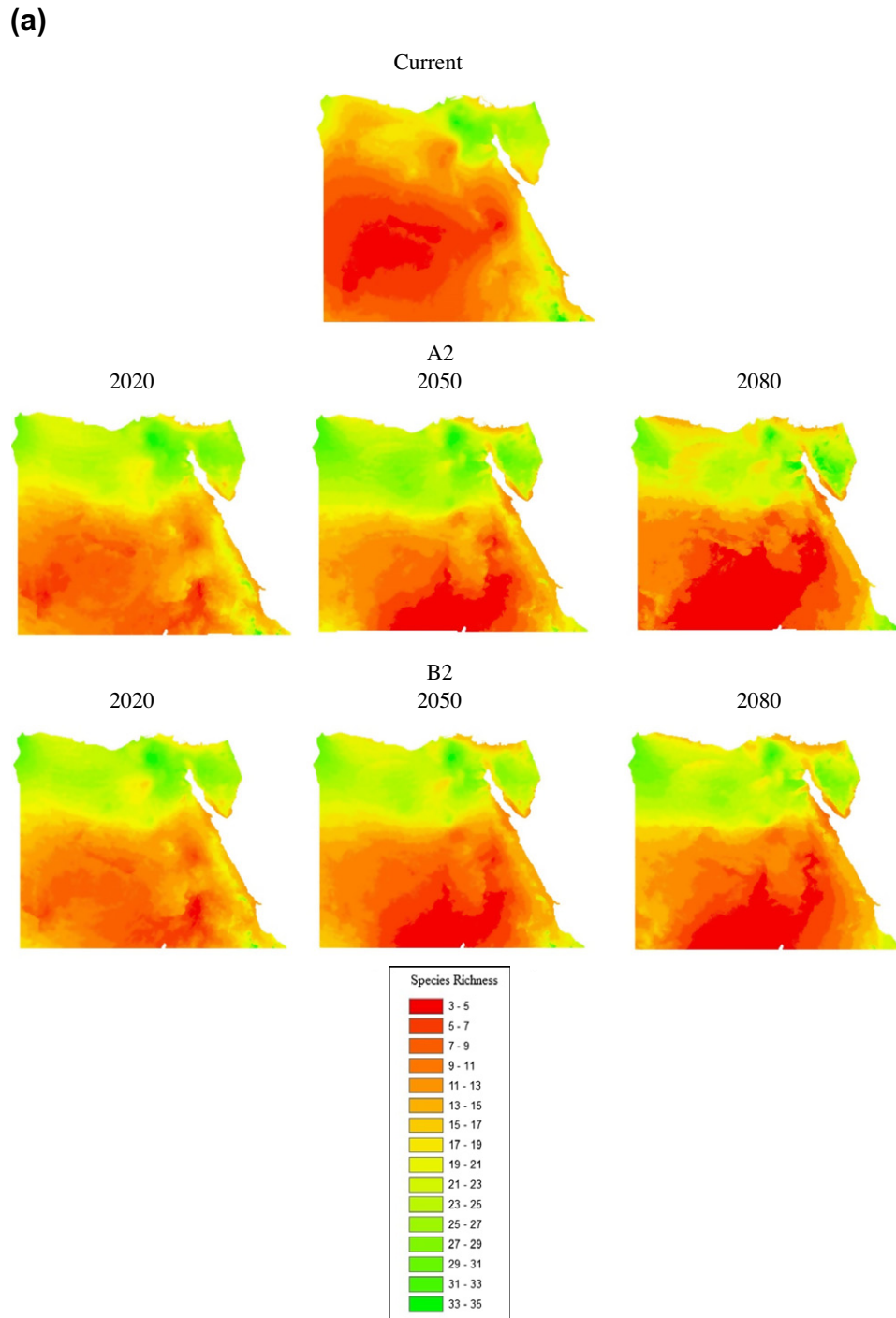
3. Results

Mammals are predicted to change their distributions substantially under future climates (Fig. 1a). Areas inland and in southern Egypt are predicted to undergo declines of 4–6 species relative to today, whereas areas in Northern Egypt are likely to increase by approximately 5 species. Most of the predicted changes concern rodents. There are also predicted to be changes in species richness of butterflies, especially in the 2080s under the A2 scenario (Fig. 1b). Large areas of Egypt are predicted to maintain low species richness, with some areas inland and to the south seeing significant decreases of 2–4 species, and Sinai a large decrease of 8–10 species. However, some areas, especially in the north, are predicted to increase in species richness slightly (by 2–4 species). There are slight differences between the A2 and B2 scenarios, but in general the B2 scenarios just appear to be happening at a slower rate. We are not expecting any species to become extinct over the next few decades, but merely to change their distribution within Egypt.

Relative to the situation under the current climate, the mean ranked score for mammal grid cells within Protected Areas across Egypt is predicted initially to decrease under the A2 scenario for the 2020s. The mean score decreases again slightly in the 2050s and then increases in the 2080s. For butterflies the mean ranked score within Protected Areas decreases in the 2020s, then increases slightly in the 2050s and again in the 2080s (Fig. 2a). This pattern of an initial decrease and then a gradual increase is also seen under the B2 scenario (Fig. 2b). The standard errors are quite large for mammals due to differences between the results of the Zonation runs.

Relative to current climate, the number of high-ranked grid cells for mammals within Protected Areas is predicted to decrease in the 2020s, but then increase in the 2050s and again in the 2080s. For butterflies, after an initial decrease in the 2020s, it is predicted to increase in the 2050s, but then decrease under the A2 scenario for the 2080s (Fig. 2c). A similar pattern is also seen for both taxa under the B2 scenario (Fig. 2d). The standard errors are fairly large for mammals currently and for butterflies in the 2080s due to large differences between the results of Zonation runs.

The conservation value of grid cells (Zonation score) varies according to the future climate-change scenario (Fig. 3), with similar changes being seen under the A2 and B2 scenarios. For mammals there is predicted to be a decreased number of areas with high conservation value, especially in Sinai and Northern Egypt, but a slight increase in conservation value in the north-eastern part of Sinai. For butterflies, the Sinai region maintains a high conserva-

(a)

Current

A2

| 2020 | 2050 | 2080 |

B2

| 2020 | 2050 | 2080 |

Species Richness

	3 - 5
	5 - 7
	7 - 9
	9 - 11
	11 - 13
	13 - 15
	15 - 17
	17 - 19
	19 - 21
	21 - 23
	23 - 25
	25 - 27
	27 - 29
	29 - 31
	31 - 33
	33 - 35

Fig. 1. Species richness maps for (a) mammals and (b) butterflies under A2 and B2 scenarios for all years. Species richness was calculated as the sum of the probabilities of occurrence. A red colour implies that a low number of species are present and a green colour indicates high species richness. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tion value in the future, but the area with high conservation value in Northern Egypt appears to decrease.

4. Discussion

Egypt's conservation efforts began with the establishment of the Environmental Affairs Agency in 1982, followed by Ras Muhamed National Park, declared in 1983, and its signing of the Rio Convention in 1992 (EEAA, 1998). Conservation of the environment and of biodiversity are therefore relatively recent activities of

government, and the $1 m-BioMAP project (funded by Italian Cooperation via Debt Swap) was the first to collate records of the various taxa, let alone use them in analyses for conservation. After the 4-year project had finished, it was not extended partly because of a lack of awareness of the role of such data in conservation decision-making. This sequence of events illustrates the dilemma in which most countries of the world find themselves. There are some existing data but it takes time and money to collate them into a usable format, even if anyone has the vision to want it done. To collect new data takes a great deal more time and money. Thus only if
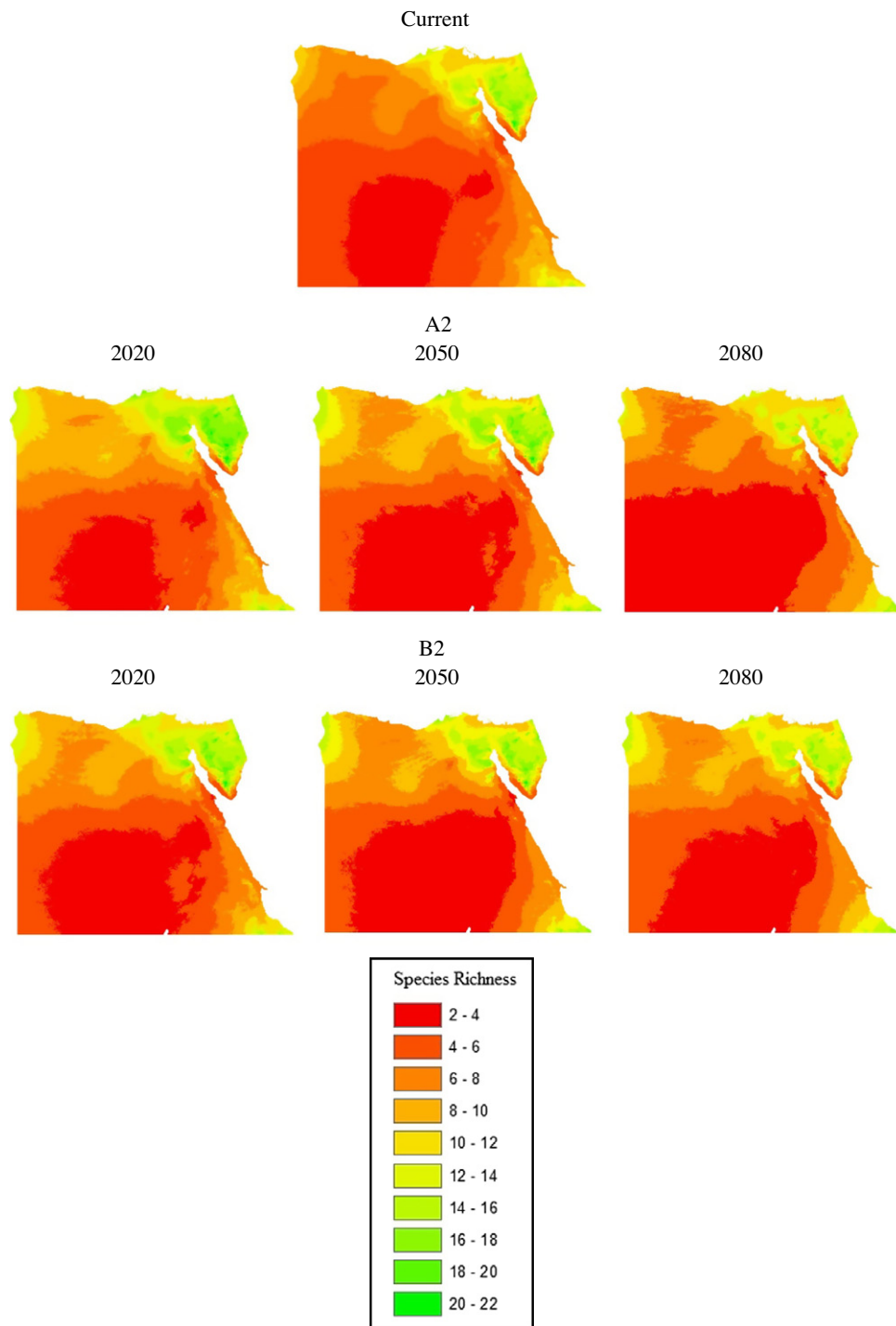
(b)

Current

A2

| 2020 | 2050 | 2080 |

B2

| 2020 | 2050 | 2080 |

Species Richness

■	2 - 4
■	4 - 6
■	6 - 8
■	8 - 10
■	10 - 12
■	12 - 14
■	14 - 16
■	16 - 18
■	18 - 20
■	20 - 22

Fig. 1. (*continued*)

one is lucky are there existing databases of records with which to perform the kind of work presented here. The best one can hope for is that there are enough records to overcome their long-recognised shortcomings of spatial and temporal bias (Newbold, 2010) and hence to enable the use of species distribution models with some reasonable degree of confidence. However, no-one actually doing conservation can afford to await the perfect dataset (MEA, 2005).

It is a similar story with the establishment of Protected Areas. There is quite a body of literature on optimal networks of Protected

Areas (Sarkar et al., 2006). In the face of climate change, it is possible to design Protected-Area networks to minimise its effects on biodiversity. Game et al. (2011) showed how one can design defensible strategies in the face of uncertainty: either look for areas where climate change is predicted to be minimised, or use environmental heterogeneity as a surrogate to indicate high biodiversity (such as areas of geophysical diversity – areas chosen on this basis in New Guinea contained 90–98% of floral biodiversity and 50–78% of faunal biodiversity), or choose an optimal balance
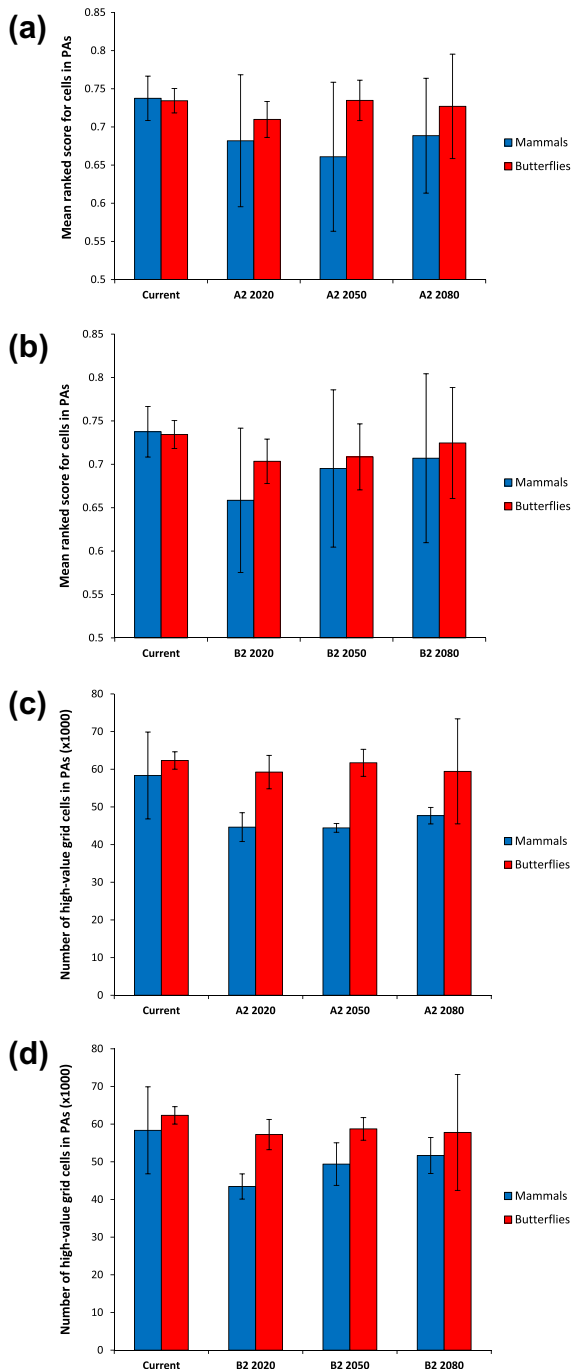
Fig. 2. Mean ranked score of cells (a and b) and number of high-ranked cells (c and d) under future climate change scenarios A2 (a and c) and B2 (b and d) scenarios (for the 2020s, 2050s and 2080s) within Protected Areas for mammals and butterflies. Averages were calculated across all Zonation runs and across all three climate models (HADCM3, NIES99 and CSIRO MK2). High-ranked cells are cells which have a ranked score >0.7.

between fragmentation and maximising environmental diversity within Protected Areas. However, these are only possibilities if you can choose where to place Protected Areas *a priori*: usually we already have an existing network, and it is only possible to adapt it, for example using linking corridors (Vos et al., 2008; Lawton, 2010). In order to do this effectively, a great deal of information is required about the species concerned (e.g. Vos et al., 2008), which is lacking for the biodiversity of most countries such as Egypt.

This study is limited to within the borders of Egypt, where there are few or no endemic mammals except possibly the recently recognised Egyptian Weasel, *Mustela subpalmata* (Basuony et al., 2010), and only two endemic butterfly species (Gilbert and Zalat, 2008). This clearly does not encompass the full geographic range of each species, known to introduce some uncertainty and error into predictions because the full range of the niche is not modelled, and the projections of future climates therefore involve extrapolating beyond the limits of the data (Thuiller et al., 2004; Barbet-Massin et al., 2010). In our case, for example, the current mean maximum temperature ranges from 25.2 to 42.1 °C, but under the A2 scenario is predicted to reach the range 31.2–48.5 by 2080. The current range of annual precipitation is 0–227 mm, but is predicted to change to 0–198 mm in the same scenario. The uncertainties involved in extrapolating outside the limits of the data will clearly vary with the taxon and range being modelled, but appear to be relatively small (Thuiller et al., 2004; Marbet-Massin et al., 2010), and we are here interested in the overall patterns of changes in species richness across 60 mammal and 35 butterfly species, rather than the specific details of individual species.

A second issue is the fact that extra-limital species, such as those from Sudan, could invade under climate change, and these potential colonists are not captured in our models (Pearson et al., 2002; Barbet-Massin et al., 2010). One response to these issues is to omit parts of the country from consideration (Sætersdal et al., 1998), but a better strategy is to model a greater range: Pearson et al. (2002) used the whole of Europe when considering plants in the UK, and Barbet-Massin et al. (2010) used North Africa and the western Palaearctic in modelling Iberian bird distributions. The recommendations are to use the entire ranges of species, or at least entire biogeographic regions. Once again in Egypt this is impossible to fulfil. There appear to be no validated reliable datasets from Sudan or Libya, for example, to match those from Egypt.

It is often claimed that it is very difficult to predict climate change effects on biodiversity because of the wide variety of influences other than merely climate on populations and hence distributions, such as interactions between species (review, see Bellard et al., 2012). Species differ in their ability to move, and the rate of adaptation to changing conditions, both of which might affect responses to climate change. Here we are not expecting any species to become extinct over the next few decades, but merely to change their distribution within Egypt. Virtually nothing is known about the dependencies of Egypt's mammal and butterfly species on other elements of the biodiversity of the country, and thus currently it would be impossible to incorporate such considerations into models of how biodiversity might be affected by climate change.

We use here species distribution modelling (using MaxEnt) together with spatial prioritization for conservation (using Zonation), a combination increasingly used to assess Protected Area networks in the face of climate change (e.g. Carvalho et al., 2010; Klorvuttimontara et al., 2011). Given what we have said above, we think this is all that many countries will be able to do, given the availability of datasets and the current state of knowledge about which of their species will move and which will not, and the linkages among species within local communities.

As far as we are aware, this is the first-ever published study of the impact of climate change on biological diversity in Egypt, although there are two studies on single species (Hoyle and James, 2005; El-Din Soultan, 2011); there are similar studies on the birds (e.g. Jetz et al., 2007) and bats of other countries (e.g. Rebelo et al., 2010; Hughes et al., 2012). We have concentrated not on predictions of extinction, but on the relative ability of the Protected Area network to conserve Egypt's fauna. Egyptian mammal and butterfly species currently have higher species richness inside Protected Areas than outside (Newbold et al., 2009). There are some strong
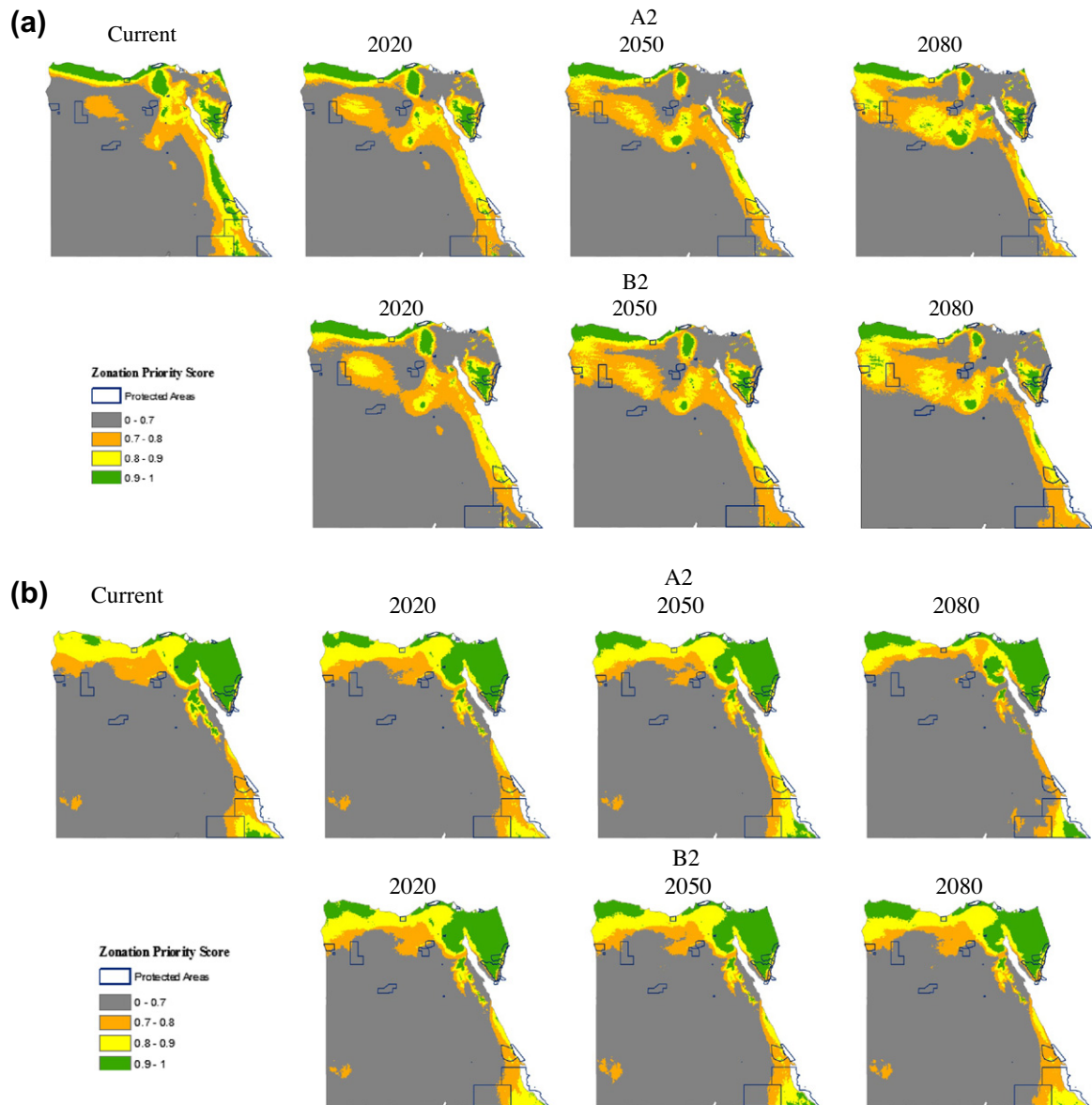
Fig. 3. Zonation priority scores of cells for (a) mammals and (b) butterflies at present and under A2 and B2 scenarios for the 2020s, 2050s and 2080s. A grey colour indicates that the score is between 0 and 0.7, amber is 0.7–0.8, yellow is 0.8–0.9 and green is 0.9–1. The Zonation score in a particular grid cell is equivalent to the conservation value of that grid cell; therefore green cells have a very high conservation value. Averages were calculated across all Zonation runs and across all three climate models (HADCM3, NIES99 and CSIRO MK2). The blue lines show boundaries of Protected Areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

spatial patterns to the predicted consequences of climate change. We can suggest which aspects of the climate are causing changes in species richness by inspecting the maps (Figs. 1 and 2) together with the MaxEnt results for individual species. The variables which consistently contributed most to the models were the annual precipitation (*sum_prec*) and the variation in the minimum temperature (*std_tmin*).
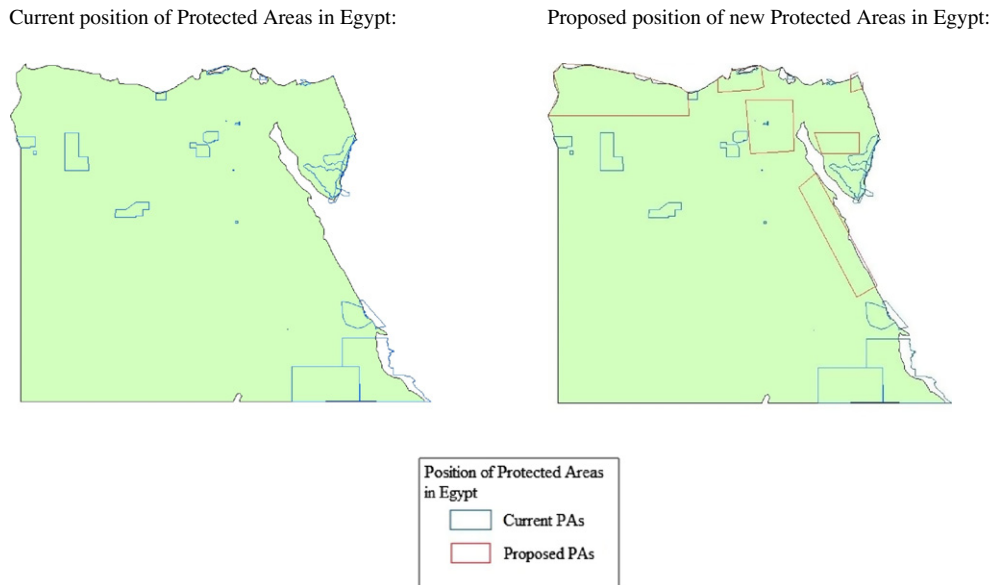
Mammal species richness is predicted to increase in northern areas of Egypt under future climate scenarios; this correlated with an increase in annual precipitation (up to 41 mm) and a decrease in minimum and maximum temperature (up to 1 °C) in this region. The predicted cooler and wetter climate here in the future may be more likely to suit most mammal species. However, areas inland and in southern Egypt are predicted to decrease by up to six species as the climate here becomes less suitable for many mammals (cf. Honnay et al., 2002; Hannah, 2008). By contrast, rodents are predicted to increase in species richness in central areas of Egypt,

presumably because they are better able to cope with the increased temperature (up to 7 °C) and decreased precipitation (up to 23 mm). Because the species distribution models were developed using only Egyptian records, we cannot estimate how many species from Sudan will migrate into southern Egypt, reducing the predicted losses in species richness.

Butterfly species appear to become slightly better suited to living in northern regions of Egypt under future climates, and less able to survive in southern and central regions. The climate models suggest that northern Egypt will become cooler (by up to 1 °C) and wetter (by up to 41 mm) in the future, leading us to believe that this climate will benefit butterflies. For example, the Olive-haired Skipper, *Borbo borbonica*, appears to increase its distribution significantly in northern Egypt under future climates.

The likely changes in distribution that we have estimated could be too small because of the nature of the data we used. Since the data consists of records from the period 1900–2007, it is possible

Current position of Protected Areas in Egypt: Proposed position of new Protected Areas in Egypt:

Position of Protected Areas in Egypt
- Current PAs
- Proposed PAs

Fig. 4. Proposed position of new Protected Areas in Egypt (shown in red) which take into account species richness and conservation value results which have been produced as part of this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that distributions have already altered in response to climate change since 1900. The climate averages derive from the period 1950–2000. Unfortunately, we cannot avoid this temporal mismatch by selecting just records collected since 1950, because there are too few: Egypt shares this dilemma with a great number of similar countries. The projected changes in the distribution of mammals and butterflies therefore may be underestimates if the 'current' distributions are a mixture of pre- and post-change responses.

The spatial pattern of the predicted changes in Egypt is important. Protected Areas in Sinai, for example, are predicted to maintain a high conservation value for mammals throughout the period. The larger mainland Protected Areas (e.g. Gebel Elba and Wadi El Allaqi) are predicted to decrease in conservation value for mammals initially, but then steadily increase up to the 2080s: thus it might be wise to invest in these Protected Areas now. Areas of the Nile Valley and Delta have high species richness and hence conservation value, but protecting them could be difficult given their long history of economic exploitation and very high human population density (Newbold et al., 2009).

Under future climate there is a large initial decrease in the relative conservation value (mean ranked scores and numbers of high ranked grid cells) of areas within the Protected Areas, but then this appears to increase gradually from the 2050s onwards. This pattern of an initial decline and then a gradual increase in relative conservation value over time is a striking result. The reason for this interesting non-linear effect of climate change is unknown. Further work is required to determine the cause. Most areas will need protection now to prevent a predicted decline in relative conservation value by the 2020s, for example by increasing the number of Protected Areas in high-risk areas and increased protection from human disturbance. By the 2080s the relative conservation value of Protected Areas is predicted to increase slightly, suggesting that Protected Areas will become more valuable for biodiversity maintenance. Our results suggest that there are six areas where new Protected Areas would help buffer the conservation network against the predicted declines in species richness and conservation value caused by climate change (Fig. 4). However, they include the major areas of population concentration in Cairo, Alexandria and the Nile Delta, and the major area of building construction along

the Mediterranean coast between Alexandria and Mersa Matrouh. This illustrates one of the conservation's dilemmas that human settlements have often been in fertile areas rich in biodiversity.

The results for mammals and butterflies for both species richness and conservation value under future climate appear to be rather similar. In general, mammals and butterflies are predicted to have high species richness in northern Egypt and lower species richness in southern Egypt. The mean ranked scores of conservation value are always higher for butterflies under future climate, but a similar pattern is seen for both taxa. A similar pattern is also seen for the number of high-priority grid cells. There is an initial decline in conservation value for both mammals and butterflies and a similar distribution of high priority cells for each taxa. However, butterflies contain many more cells with a value greater than 0.9 and mammals occupy more non-coastal areas. To prevent the initial decline in conservation value, management decisions will probably need to be taken; this should perhaps include considering an increase in the number of Protected Areas in the relevant areas, designed to maximise resilience to climate change. It would also be useful to have dynamic conservation plans that can allow Protected Areas to shift in the future with climate change (Schwartz, 2012). The outlook for mammals appears to be fairly good, but conservation efforts may need to focus on preventing species richness declines in southern Egypt and preventing declines in areas of high conservation value by increasing the effectiveness of current Protected Areas and creating new ones. For butterflies, the outlook appears also to be good since areas of high conservation value appear to be similar in the 2080s. Current conservation efforts may be enough, perhaps coupled with action to prevent the small decline in species richness in southern and central Egypt.

At present our results are conservative since we could not incorporate additional factors into our projections such as species interactions, vegetation or demographic changes. A next step might be to use topographical, elevational and land-cover data to provide a better understanding of which habitat types are most susceptible to future climate change, and to try to assess the abilities of each species to move in response to climate change, for example between elevational bands (Menendez et al., 2007; Van Mantgem and Stephenson, 2007). As more data becomes available for Egypt (with datasets for another 10 taxa soon to be finalised), it will be

instructive to include a wider range of taxa: Kremen et al. (2008) used six taxa (ants, butterflies, herptiles, mammals and plants) in their study of Madagascan biodiversity. Conservation management of Protected Areas in the future should include information on the responses of species to climate change: we cannot assume that the distributions of species will be stationary (Klorvuttimontara et al., 2011). Protected Areas that are predicted to decline in relative conservation value in the future may benefit from actions to reduce human disturbance and to increase connectivity, since well-connected areas may allow species to persist for longer (Cabeza and Moilanen, 2001). The conservation value of many Egyptian Protected Areas is predicted to increase in the longer-term future, so it is vital that long-term protection of these areas is guaranteed.

Acknowledgements

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2012.11.025.

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