From climate change predictions to actions – conserving vulnerable animal groups in hotspots at a regional scale.

Silvia Benoliel Carvalho, José Carlos Brito, Eduardo J. Crespo, Hugh Possingham

▶ **To cite this version:**

Silvia Benoliel Carvalho, José Carlos Brito, Eduardo J. Crespo, Hugh Possingham. From climate change predictions to actions – conserving vulnerable animal groups in hotspots at a regional scale.. Global Change Biology, Wiley, 2010, 16 (12), pp.3257. 10.1111/j.1365-2486.2010.02212.x . hal-00552617

HAL Id: hal-00552617

https://hal.archives-ouvertes.fr/hal-00552617

Submitted on 6 Jan 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

From climate change predictions to actions – conserving vulnerable animal groups in hotspots at a regional scale.

For Review Only

Journal:	*Global Change Biology*
Manuscript ID:	GCB-09-0856.R1
Wiley - Manuscript type:	Primary Research Articles
Date Submitted by the Author:	19-Jan-2010
Complete List of Authors:	Carvalho, Silvia; CIBIO - Centro de Investigação em Biodiversidade e Recursos Genéticos da Universidade do Porto; The University of Queensland, The Ecology Centre Brito, José; CIBIO - Centro de Investigação em Biodiversidade e Recursos Genéticos da Universidade do Porto Crespo, Eduardo; Faculdade de Ciências da Universidade de Lisboa, Departamento de Biologia Animal Possingham, Hugh; University of Queensland, The Ecology Centre
Keywords:	climate change, Iberian Peninsula, ensemble modelling, species distribution model, vulnerability, herptiles
Abstract:	Current climate change is a major threat to biodiversity. Species unable to adapt or move will face local or global extinction and this is more likely to happen to species with narrow climatic and habitat requirements and limited dispersal abilities, such as amphibians and reptiles. Biodiversity losses are likely to be greatest in global biodiversity hotspots where climate change is fast, such as the Iberian Peninsula. Here we assess the impact of climate change on 37 endemic and nearly endemic herptiles of the Iberian Peninsula by predicting species distributions for three different times into the future (2020, 2050 and 2080) using an ensemble of bioclimatic models and different combinations of species dispersal ability, emission levels and global circulation models. Our results show that species with Atlantic affinities that occur mainly in the North-western Iberian Peninsula have severely reduced future distributions. Up to 13 species may lose their entire potential distribution by 2080. Furthermore, our analysis indicates that the most critical period for the majority of these species will be the next decade. While there is considerable variability between the scenarios we believe that our results provide a robust relative evaluation of climate change impacts among different species. Future evaluation of the vulnerability of individual species to climate change should account for their adaptive capacity to climate change, including factors such as physiological climate tolerance,

	geographical range size, local abundance, life cycle, behavioural and phenological adaptability, evolutionary potential and dispersal ability.

scholarONE™ Manuscript Central

For Review Only

Title

From climate change predictions to actions – conserving vulnerable animal groups in hotspots at a regional scale.

Running title

From climate change predictions to actions

Authors

Sílvia B. Carvalho[1,2,3] José C. Brito[1], Eduardo J. Crespo[2,5] & Hugh P. Possingham[3,4]

1 – CIBIO - Centro de Investigação em Biodiversidade e Recursos Genéticos da Universidade do Porto, R. Padre Armando Quintas, 4485-661 Vairão, Portugal

2 – Departamento de Biologia Animal, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, 1749-016 Lisboa, Portugal.

3 - The University of Queensland, the Ecology Centre, St Lucia QLD 4072, Australia

4 - The University of Queensland, the School of Maths and Physics, St Lucia QLD 4072, Australia

5 - CBA, Centro de Biologia Ambiental da Universidade de Lisboa, Campo Grande, 1749-016 Lisboa, Portugal

Corresponding author: Silvia B. Carvalho

email: silviacarvalho@mail.icav.up.pt

Telephone: +351 252660416

Fax: +351 252661780

Other authors email address:

José Carlos Brito: jcbrito@mail.icav.up.pt

Eduardo J. Crespo: ejcrespo@fc.ul.pt

Hugh P. Possingham: h.possingham@uq.edu.au

Key words: amphibians, reptiles, climate change, Iberian Peninsula, ensemble modelling, species distribution model, vulnerability, adaptive management

For Review Only

Abstract

Current climate change is a major threat to biodiversity. Species unable to adapt or move will face local or global extinction and this is more likely to happen to species with narrow climatic and habitat requirements and limited dispersal abilities, such as amphibians and reptiles. Biodiversity losses are likely to be greatest in global biodiversity hotspots where climate change is fast, such as the Iberian Peninsula. Here we assess the impact of climate change on 37 endemic and nearly endemic herptiles of the Iberian Peninsula by predicting species distributions for three different times into the future (2020, 2050 and 2080) using an ensemble of bioclimatic models and different combinations of species dispersal ability, emission levels and global circulation models. Our results show that species with Atlantic affinities that occur mainly in the North-western Iberian Peninsula have severely reduced future distributions. Up to 13 species may lose their entire potential distribution by 2080. Furthermore, our analysis indicates that the most critical period for the majority of these species will be the next decade. While there is considerable variability between the scenarios we believe that our results provide a robust relative evaluation of climate change impacts among different species. Future evaluation of the vulnerability of individual species to climate change should account for their adaptive capacity to climate change, including factors such as physiological climate tolerance, geographical range size, local abundance, life cycle, behavioural and phenological adaptability, evolutionary potential and dispersal ability.

For Review Only

Introduction

Anthropogenic driven climate change is evident and for the next two decades a warming of at least 0.2°C per decade is projected (IPCC, 2007) with associated changes in precipitation patterns. Throughout the history of Earth, climate has changed and species have coped and adapted to these changes, but current climate change is threatening biodiversity because it is fast compared to most past changes (Thomas *et al.*, 2004). Current climate warming was considered the second most important threat to terrestrial biodiversity, only exceeded by land-use change (Sala *et al.*, 2000).

Climate change have been reported to affect many aspects of populations: physiology, distribution, phenology, behaviour and propensity for local extinction (Hughes, 2000, Walther *et al.*, 2002, McCarty, 2002, Root *et al.*, 2003, Parmesan, 2006). Species may be able to adapt to climatic changes via ecological (Root *et al.*, 2005) or evolutionary processes (Bradshaw *et al.*, 2006, Skelly *et al.*, 2007). However, species unable to achieve a sufficient level of adaptation will likely face local or global extinction and this is more likely to happen to species with restricted climate and habitat requirements, limited dispersal abilities and ectothermal physiology (Walther *et al.*, 2002, Thomas *et al.*, 2004, Massot *et al.*, 2008).

Amphibians and reptiles are considered one of the most vulnerable taxonomic groups to climate change (Gibbons *et al.*, 2000, Carey *et al.*, 2003, Araújo *et al.*, 2006, Wake, 2007). Climate warming is projected to induce a) changes in abundance; b) fragmentation of suitable habitats; c) changes in the timing of life-cycle events, such as hibernation, aestivation and breeding (Blaustein *et al.*, 2001, Chadwick *et al.*, 2006) and d) the spread of agents of infectious diseases such as the chytridiomycete fungus (Pounds *et al.*, 2006, Bosch *et al.*, 2007, Wake, 2007). The interaction of these impacts causes disruptions in population and metapopulations dynamics, which ultimately may lead to changes in distribution.

For Review Only

The impact of global warming on biodiversity is likely to be more severe in regions rich in endemic species that are also predicted to be affected by dramatic climatic changes. The Mediterranean Basin is a particularly susceptible region: it is a biodiversity hotspot holding many endemic species (Médail *et al.*, 1999, Myers *et al.*, 2000, Mittermeier *et al.* 2005) and climate predictions for this region include a substantial rise in temperature and a drastic drop in rainfall, contributing to desertification (MIO-ECSDE, 2003). The synergistic effect of climate change with other threats to biodiversity makes this region one of the most vulnerable in the world (Sala *et al.*, 2000).

The Iberian Peninsula, in particular, is a Mediterranean sub-region with many endemic species. The high biodiversity derives from the fact that this area was one of the major glacial refugia in Europe during the Pleistocene (Hewitt, 1996) and a diversification centre afterwards (Gómez *et al.*, 2006, Pinho *et al.*, 2007). Biodiversity richness in this area is also influenced by the climatic heterogeneity, since the climate transition between Atlantic and Mediterranean allows the co-occurrence of species with African and Euro-Siberian affinities, which means that the Iberian Peninsula is a biogeographic crossroad (Spector, 2002).

In face of climate change challenges, conservation organizations are being asked to take proactive measures to mitigate impacts on biodiversity. To select appropriate measures we need to be able to predict the impact of climate change on biodiversity and evaluate the ability of biodiversity to adapt to those impacts. The combination of this information can be used to determine biodiversity vulnerability, which in turn becomes the basis for prioritizing species and defining management strategies (Kareiva *et al.*, 2008).

Species distribution models (SDMs) are frequently used to assess the impacts of climate change on species distributions (*e.g.* Araújo *et al.*, 2006). These statistical tools relate present day distributions with current environmental conditions and then use future potential climate conditions to predict future species distributions (Pearson *et al.*, 2003). Predicting the impacts

For Review Only

of climate change on species is a challenging task because SDMs include parameters with many sources of uncertainty (Webster *et al.*, 2002) mostly related to: a) the statistical tool used for modelling species distributions; b) the global circulation models used to predict future climate conditions (Thuiller, 2004, Pearson *et al.*, 2006, Beaumont *et al.*, 2008); and c) uncertainty derived from scale effects (Seo *et al.*, 2009). Recently, advances in SDMs have made it possible to significantly reduce prediction uncertainties. For example, several robust statistical modelling methods have been developed to predict species distributions (see Elith *et al.*, 2006 for review), while advanced methodologies in ensemble forecasting allow us to overcome the problem of variability in predictions made by different modelling techniques or different global circulation models (Pearson *et al.*, 2006, Araújo *et al.*, 2007, Marmion *et al.*, 2009). Additionally, climate predictions have been improved at smaller spatial scales (Hijmans *et al.*, 2005).

In this study, we will evaluate potential impacts of climate change on the distribution of amphibians and reptiles in the Iberian Peninsula. We focus on endemic and nearly endemic species, the later defined as species that have aproximatelly more than two thirds of their entire range in the Iberian Peninsula. We then use information about species adaptability and vulnerability to make conservation recommendations.

Araújo *et al.* (2006) identified the Iberian Peninsula as one of the areas in Europe where amphibians and reptiles are likely to undergo major contractions in their ranges. Therefore, a detailed analysis of the Iberian Peninsula at a scale appropriate for establishing management strategies is urgently needed. We complement Araújo *et al.*'s (2006) European-wide research by providing a more detailed analysis of the impact of climate change on amphibian and reptile's distribution within the Iberian Peninsula. In particular, we used the most recent distribution data which are geographically more detailed than the one used in Araújo *et al.* (2006) (10x10 km in opposition to 50x50km) and incorporate recent taxonomic discoveries,

For Review Only

that significantly increases the number of endemics (21 species vs. 12 species). Additionally, we project species ranges to three times in the future (2020, 2050, 2080 instead of 2050 only), which may assist conservation decision making in terms of prioritizing the allocation of conservation funds through time.

We provide specific recommendations to conservation practitioners for enhancing the probability of species persistence by answering the following questions: In the Iberian Peninsula, which endemic and nearly endemic amphibian and reptile species are predicted to lose and gain suitable habitat in the future? For species predicted to lose suitable habitat, is the loss rate constant throughout time or are there more critical periods? Which areas will be more impacted by species loss? Which species should be under priority conservation action? Which conservation measures are most likely to increase the probability of species persistence?

Methods

Study area

The study region is the continental Iberian Peninsula, situated in the extreme southwest of Europe (bounded by 9º32' to 3º20'E and 35º56' to 43º55'N). With an area of 582 860 km^2, it includes the continental territories of Portugal and Spain. It is bordered to the south and east by the Mediterranean Sea and to the north and west by the Atlantic Ocean. The Pyrenees and the Strait of Gibraltar separate most of the region from the remainder of Europe and Africa, respectively (Figure 1). The dominant climate type of the region is Mediterranean, but the north and northwest of the Iberian Peninsula and the major mountain systems are characterised by an Atlantic climate.

Species and distribution data

For Review Only

Distribution data for 37 endemic and nearly endemic species (15 amphibians and 22 reptiles) were collected from the most recent herpetological atlases of Portugal (Loureiro *et al.*, 2008) and Spain (Pleguezuelos *et al.*, 2002), which are referenced to the UTM grid of 10x10 km. Taxonomy was defined according to the most recent revision of the taxonomic list in Carretero *et al.* (2009). We excluded from our analysis records from the Portuguese atlas for *Triturus marmoratus* because that data does not distinguish between *Triturus marmoratus and T. pygmaeus*. We followed the same method for Portuguese records of *Pelodytes punctatus* because they represent two species: *Pelodytes punctatus and P. ibericus.* Our data contained only two records of *Iberolacerta martinezricai* so we were unable to develop a plausible predictive model.

Climate data

Current bioclimatic data were downloaded from WorldClim database (Hijmans *et al.*, 2005) which is a set of global climate layers generated through interpolation of climate data from weather stations. We used nine variables that were not tightly correlated with each other (with a Pearson correlation coefficient between them lower than 0.75): temperature seasonality, maximum temperature of warmest month, minimum temperature of coldest month, temperature annual range, annual precipitation, precipitation of wettest month, precipitation of driest month, precipitation seasonality and altitude. All variables were downloaded in a 2.5 arc-minute resolution. We converted these data to match with the same grid format as the species distribution data by averaging the variable's values inside each grid cell.

We used future climate data for three Global Circulation Models (GCM) (CCCMA, HADCM3 and CSIRO) and two IPPC 3rd assessment storylines (A2 and B2). The IPCC storylines describe the relationships between the forces driving greenhouse gas and aerosol

For Review Only

emissions such as demographic, social, economic, technological, and environmental developments (IPCC-TGICA, 2007). The two storylines used for this study assume regionally oriented economic growth, with population and economic growth being higher in A2 than B2. Future climate data were downloaded from WorldClim, for three different future years (2020, 2050 and 2080) creating six storyline-GCM combinations for each future year. We downloaded monthly averages of maximum and minimum temperatures and total precipitation and calculated the bioclimatic variables according to the same methodology used to calculate them for current climate conditions (Hijmans *et al.*, 2005).

Species distributions: current predictions and future projections

We used a set of nine modelling techniques to predict the distribution of each of the 37 species in four different times (current, 2020, 2050 and 2080): Maximum Entropy (MXT), Generalised Linear Models (GLM), Generalised Additive Models (GAM), Classification Tree Analysis (CTE), Artificial Neural Networks (ANN), Generalised Boosting Model (GBM), Breiman and Cutler's random forest for classification and regression (RF), Mixture Discriminant Analysis (MDS) and Multiple Adaptive Regression Splines (MARS).

To produce Maximum Entropy models we used Maxent software (Phillips *et al.*, 2004). Maxent estimates the range of a species with the constraint that the expected value of each variable (or its transform and/or interactions) should match its empirical average, *i.e.* the average value for a set of sample points taken from the species-target distribution (Phillips *et al.*, 2006, Phillips *et al.*, 2008). We used the default "auto features" option, logistic output, the recommended default values for the convergence threshold (10^{-5}) and the maximum number of iterations (500).

For Review Only

The remaining eight models were built within BIOMOD (Thuiller *et al.*, 2009) . BIOMOD is a collection of functions running within the R software v. 2.8.1 (R Development Core Team 2008) for ensemble forecasting of species distributions and a summary of model statistics is described in Thuiller *et al.,* (2009). The majority of model-techniques requires data about presences and absences, thus we determined pseudo-absences for each species by using the "random strategy" in BIOMOD. The number of selected pseudo-absences for each species was equal to the number of its occurrences, whenever possible. In cases where the number of locations where species was not recorded was less than the number of occurrences, we selected all non-occurrences as pseudo-absences. All models were produced using default BIOMOD parameters where possible (Thuiller *et al.,* 2009). Further parameters were as following: GLMs were generated using quadratic terms and a stepwise procedure with the AIC criteria. GAMs were generated with a spline function with 4 degrees of smoothing. ANNs were produced with two cross-validations. BIOMOD allows evaluation of model performance on different data split runs and then allows using 100% of the data to make a final calibration of the models for prediction. Thus we randomly assigned 80% of occurrence data to train the model with the remaining 20% for testing. Each model was run ten times to avoid bias resulting from randomly splitting the data into training and testing.

To evaluate the performance of individual models from each technique, we calculated the area under the receiver operating characteristic curve (AUC) (Zweig *et al.*, 1993, Fielding *et al.*, 1997). For each of the 37 species we produced nine models for the current time and climate (with different modelling techniques) and 54 models (combination of nine modelling techniques, three GCM and two storylines) for each of the three times in the future (2020, 2050 and 2080), in a total of 171 models per species.

For each year in the future (2020, 2050 and 2080) we calculated an ensemble forecast for current time and for each IPCC scenario for the future (A2, and B2). For this purpose, we

For Review Only

used weighted average consensus method based on AUC values, because this method is considered to significantly improve the predictive accuracy of single models (Marmion *et al.*, 2009). Thus, AUCs values of each model technique were assigned the weights of the weighted average in order to enhance contributions of those models with higher model performance values (equation 1).

$$WA_i = \frac{\sum_m (AUC_m \times p_{mi})}{\sum_m AUC_m} \quad \text{(equation 1)}$$

where i is the index of the grid cell, m is the model technique and p is the probability of occurrence of the species (according to model m in grid cell i).

To investigate if species ranges were predicted to contract or expand, we needed to convert the consensus forecasted probabilities of occurrence in each year to a binary value of predicted presence/absence. For each model technique, we calculated the threshold of the receiver operating characteristic curve that maximizes both correctly predicted presences and absences, relative to the evaluation data (Liu *et al.*, 2005). Subsequently, we determined a consensus threshold (CT) by calculating the weighted average threshold, assigning the AUC value of each model as a weight (equation 2).

$$CT = \frac{\sum_m (AUC_m \times t_m)}{\sum_m AUC_m} \quad \text{(equation 2)}$$

where m is the model technique and t_m is the optimised threshold of model m.

Potential range shifts of each species and time period were measured under two extreme dispersion scenarios: unlimited dispersal (scenario D), assuming that species can disperse to

For Review Only

any grid cell with suitable habitat, and no dispersal (scenario ND), assuming that species are not capable to disperse even if suitable habitat is available. To predict species presence under the D scenario, we transformed the consensus probability value in each grid cell into 0 if it was lower than CT and to 1 if it was equal to or higher than CT. To predict species presences under the ND scenario, we transformed predicted presences to absences in grid cells where species is not presently predicted to occur. We evaluated the degree of uncertainty of projections for each year and scenario by calculating the standard deviation of predicted occurrence of species by grid cell.

Subsequently, we calculated predicted species richness in each grid cell for the three future periods. Future species richness was estimated by summing the number of species predicted to occur in each grid cell under each of the storylines and the dispersion scenarios. Species turnover (T) is the dissimilarity index between the present and future species composition of a given area. It accounts both for species gain and losses and its relation to the overall number of species occurring in the grid cell in present and future. Thus, a turnover value of 0 indicates that the predicted assemblage in the future would be the same as the current assemblage, whereas a turnover value of 100 indicates that the assemblage would be completely different under climate change. To determine it, we first calculated the number of species lost (L), *i.e.*, the number of species predicted to lose suitable habitat in each grid cell, and the species gain (G), *i.e.*, the number of species predicted to gain suitable habitat in each grid cell. Percentage of species turnover by grid cell was then calculated according to equation 3.

$$T = 100x\frac{L+G}{SR+G}, \qquad \text{(equation 3)}$$

where SR is the current predicted species richness.

For Review Only

Results

Model predictions within different modelling techniques, GCMs, and storylines showed high variability in the projection of range shifts, with most species being projected to both lose and gain suitable habitat, depending on the scenario (supplementary material A.1 and A.2). However, when analysing the ensemble model results (Tables 1 and 2), we found that 46% of the species are consistently predicted to have a smaller distribution in both storylines (9 amphibian species and 8 reptile species), 28% of the species are consistently predicted to have a larger distribution (3 amphibian species and 8 reptile species) and the remaining species show increases and decreases depending in the time period and storyline. For example *Algyroides marchi* is predicted to have a smaller distribution until 2050 and then increase its distribution by 2080, while, *Alytes cisternasii* and *Lissotriton boscai* are predicted to have a larger distribution until 2020 and then have a smaller distribution.

Several species are predicted to lose a significant fraction of their current range (Figure 2) and 10 species are predicted to lose their entire suitable distribution at some time in both storylines. Three other species are predicted to lose all suitable range in one of the storylines only (Table 3). Surprisingly 5 to 10 of the 13 species that are predicted to lose all their suitable distribution lose it by 2020 (Table 3). Additionally, 9 of these species are also threatened by other causes, and currently considered “critically endangered”, “endangered” or “vulnerable”, in Portuguese or Spanish red data books (Tables 1 and 2).

If we assume that species have no ability to disperse, 34 species are predicted to contract their distribution and 10 species are predicted to completely lose their entire distribution in both storylines.

It is noteworthy that for species predicted to have a smaller distribution in the future, both the magnitude of contraction and the rate of contraction differ between species (Figure 3). While for most contracting species, the rate of range contraction is greater now (until 2020), for

For Review Only

some species there is almost a constant rate of predicted distribution loss (*e.g. Rana iberica*), while for a minority of species the period of greatest contraction is later (*e.g Psammodromus algirus*).

Predicted patterns of species richness are substantially different between the two dispersion scenarios, but higher species richness was commonly predicted in south-western Iberian Peninsula, the Central System mountain range and Morena Mountains (Figures 4 and 5). Major species gain, in the unlimited dispersion scenario, was predicted for the central plateaus, the central-western coast of the Iberian Peninsula, and the Cantabrian Mountains (Figure.6). Major loss of species ranges is predicted for the Atlantic climate regions, mostly along the northwest of the Iberian Peninsula and the main mountain ranges, such as the Central System and the Morena Mountains (Figure. 6). Spatial patterns of predicted species richness are similar in both storylines, although storyline B2 predicted slightly higher species losses for 2020 and storyline A2 predicted higher species loss for 2080 (Figures 4 and 5).

Discussion

Main findings and relation with previous projections

Our results suggest that climate change might have serious impacts on the distribution patterns of the endemic and nearly endemic amphibians and reptiles of the Iberian Peninsula, particularly for species with Atlantic climate affinities such as *Chioglossa lusitanica*, *Rana iberica and Vipera seoanei* and particularly high altitude species with Atlantic climate affinities such as, *Rana pyrenaica, Iberolacerta monticola, I. aranica, I. aurelioi,* and *I. bonnali*. It is also possible that other species may be more affected by climate change than predicted by the models, such as *Iberolacerta cyreni*. This species is an endemic with a current range restricted to the Gredos Mountains in Spain. However, the ensemble model for

For Review Only

this species predicted a current range much larger than probably the one where the species actually occurs. This indicates that predicted future range may also be overestimated. On the other side, models for *Pelodytes ibericus, Triturus marmoratus and T. pygmaeus* were built only based on Spanish records, although they also occur in Portugal. This methodological caveat may have conduced to an under estimation of current and future ranges of those species.

Our analysis indicates that the most critical period for the majority of these species will be the next decade. This result emphasises the need for immediate conservation action in the Iberian Peninsula to ameliorate the impact of climate change.

Previous macroscale studies have called attention to the vulnerability of biodiversity in the Mediterranean basin. This region was considered one of the most vulnerable in the world (Sala *et al.*, 2000) and one of the biodiversity hotspots likely to undergo major losses due to climate change, along with the Cape Floristic Region, the Caribbean, Indo-Burma, Southwest Australia, and the Tropical Andes (Malcolm *et al.*, 2006). The Iberian Peninsula is considered the Mediterranean sub-region most likely to be affected by future climate change (EEA, 2004). Our analysis confirm the vulnerability of species occurring in the Iberian Peninsula to climate change, but curiously, species with Atlantic climate affinities were predicted to be more affected by climate change then the Mediterranean ones. The Atlantic climate region is much more restricted in the Iberian Peninsula then the Mediterranean. Due to predicted drops in precipitation and temperature raise it is likely that the all Iberia became dominated by a Mediterranean climate. Thus, it seems logical that Atlantic species become more affected by climate change then the Mediterranean ones. Climate change impacts on Atlantic species was exacerbated by the region being a peninsula so dispersal out of the region to other Atlantic climate regions is restricted. Similar patterns should be found in other Mediterranean Peninsulas that present different climatic types (*e.g.* the Italian Peninsula and the Balkans).

For Review Only

Our results are consistent with those found by Araújo *et al.* (2006), in the sense that climate change is predicted to cause a major contraction in the distribution of a considerable number of amphibian and reptile species in the Iberian Peninsula. However, our results revealed that major losses for endemic and nearly endemic species will occur in substantially different areas than the ones predicted by Araújo *et al.* (2006) for the all amphibians and reptiles. We predict that the north-west of the region, the Central System and the Morena Mountains will lose many species in contrast to their results where there is expected to be species gain. The reasons for this difference may be our focus on endemic and nearly endemic species rather than all species, but it could also be differences in spatial scale or methods used to construct the ensemble models. Dissimilarities in areas predicted to gain species may also be related to the colonization of non endemic or nearly endemic species and non Iberian species not included in our analysis. These divergent results highlight the importance of finer-scale analyses for areas identified as vulnerable in broader continental-scale studies.

Interestingly, a previous study of climate change threats to plant diversity in Europe (Thuiller *et al.*, 2005) also identified the Iberian Peninsula as one of the European regions likely to undergo major species loss. Garzón *et al.* (2008) identified the north and northwest of the Iberian Peninsula and the main mountain ranges, as the Iberian areas likely to have the highest tree species loss, which is partially coincident with our results. Thus, if changes in vegetation communities are also predicted, it means that amphibians and reptiles will face a synergistic impact of climate and habitat change, which ultimately will also be coupled with the impact of changes in biotic interactions resulting from changes in the community of species. These results also suggest that the impacts of climate change on species ranges might be similar across different biodiversity groups that occur in the same area, which calls for the need to evaluate possible climate change impacts on those groups.

For Review Only

From predicted impacts (models) to vulnerability

Our dramatic predictions should be interpreted with caution given all the uncertainties in the process: the statistical methods used for modelling species distributions, the global circulation models used to predict future climate conditions (*e.g.* Araújo *et al.*, 2007, Beaumont *et al.*, 2008), the scale of the analysis (Seo *et al.*, 2009), and specific dispersal abilities. Additionally species distribution models disregard important biological parameters that ultimately are the determinants of species capability to adapt to climate change.

Different modelling techniques, GCM and storylines provided fairly different results for the number of predicted occurrences of a species. The ensemble methodology allows us to distinguish the strongest signal emerging from the noise associated with different model outputs but it is not immune from uncertainty. Taking uncertainty into account, for example by using as an uncertainty measure the standard deviation of the total number of occurrences predicted by the different models for each species (appendix 1A and A2), the most likely impact of climate change will be on species whose ranges are predicted to contract more (relatively to their current extent), or to become more restricted (considering their future absolute extent) with less uncertainty. For example, analysing only the year 2020 projections for storyline A2, species that fulfil both criteria are *Discoglossus galganoi* (considering the species whose ranges are predicted to contact more) and *Iberolacerta aranica*, (considering the species whose ranges are predicted to become more restricted or disappear).

The scale of analysis may also be a relevant limitation in determining the impact of climate change, because the scale used does not account for microhabitat variability within sites. This constraint is quite relevant in the case of amphibians and reptiles because they might find suitable habitat, for instance, in small ponds, water tanks, below stones or underground (Kearney *et al.*, 2009). Also, the scale of the analysis probably obscures altitudinal

For Review Only

microclimatic gradients which might allow species to move towards future suitable habitats without the need to disperse long distances.

Specific dispersal abilities may strongly determine the impacts of climate change on the future distribution of species. However, given that this parameter is difficult to determine for every species, we predicted future distributions under the assumptions of maximal and minimal possible dispersal ability for each species. We recognize that both of these assumptions are unrealistic, but they allow us to predict the largest and smallest possible future ranges. A more realistic prediction would probably be somewhere in the middle of these two extremes, but we cannot make an exact prediction with high level of certainty.

Assuming these limitations we do not argue that species predicted to completely lose their distribution under our analysis will go extinct. Rather, we consider that the degree, the certainty and the time of predicted range contractions provides a relative measure of the magnitude of the impact of climate change on each species. Ultimately, the vulnerability of a species to a given impact will depend also on the species resistance, *i.e.* the ability of a species to withstand an environmental perturbation, and resilience, *i.e.* the ability of a species to adapt and recover from a perturbation (Isaac *et al.*, 2008, Williams *et al.*, 2008,). Thus, prioritizing species for management actions would require a further analysis of the specific factors that determine resistance and resilience. In general, the species traits that are predicted to promote species resistance to climate change are physiologic climatic tolerance (Calosi *et al.*, 2008), geographical range size and local abundance.

Overall, reptiles are usually considered more resistant to global warming effects than amphibians because they have evolved a set of adaptations to water scarcity, such as eggs with calcareous shells (while amphibian eggs are enclosed by simple gelatinous membranes), and the excretion of metabolic wastes in the form of urea or uric acid, which is an adaptation to retain body-water (Gibbons *et al.*, 2000). Additionally, most reptiles are not dependent on

For Review Only

water for reproduction. Although more specific climatic tolerances might be difficult to determine, they may be inferred by morphological traits or by the complete climatic envelope of species. Also, the climatic envelope of phylogenetic related species might provide some clues, if one considers niche conservatism (Hawkins *et al.*, 2007). For example, species belonging to clades that evolved under warm environments may be more tolerant to global warming.

Species with restricted ranges are relatively more vulnerable to climate change because contractions of their small range will not be balanced elsewhere. From this point of view, species with very restricted distributions predicted to completely lose suitable habitat in the Iberian Peninsula such as *Iberolacerta aranica*, *I. aurelioi*, and *Rana pyrenaica* may be more impacted by climate change than more widespread Iberian species such as *Lissotriton boscai* or *Chalcides bedriagai*.

Demographic parameters are also important factors in determining resistance to climate change (Keith *et al.*, 2008). Species with restricted ranges but with high local abundance may have more chances to adapt because genetic variation and potential response to selection pressures are positively correlated with population size. Thus, biological traits that regulate abundance, such as reproductive rates, age of female sexual maturity and life span length are also relevant. *Discoglossus galganoi* and *Podarcis bocagei* are species predicted to completely lose their range in the Iberian Peninsula but have high abundance and reproductive rate, and consequently will probably be less impacted by climate change than the others will.

The adaptive capacity (or plasticity) of a species describes the intrinsic ability of a species to adapt to changing conditions. Species might be able to adjust their behaviour and phenology by switching periods of daily activity, aestivation and hibernation towards more favourable climatic conditions (Parmesan, 2007). Species might also be able to evolve traits that allow

For Review Only

them to adapt to different climatic conditions (Harte *et al.*, 2004, Bradshaw *et al.*, 2006). Adaptation ability may be species-specific, however, the current knowledge is insufficient to determine which species are more able to adapt and further studies and monitoring are required to fully understand it.

Species might also adapt to novel climate conditions by dispersing to other areas (Thuiller, 2004, Massot *et al.*, 2008). Dispersion ability has been identified as one of the most decisive parameters in determining species resilience to climate change as species with greater dispersion ability may be able to track climate transitions. However this parameter is also one of the most difficult to determine. A growing body of literature proposes a vast collection of complex models to predict dispersion ability (reviewed by Thuiller *et al.*, 2008) but these require detailed data on an array of ecological processes that usually are unavailable for large numbers of species.

A preliminary analysis of the model results and previous considerations indicate that species requiring more conservation attention under a climate warming perspective may be *Rana pyrenaica*, *Rana iberica* and *Calotriton asper* , within the amphibians, and *Iberolacerta aranica*, *Iberolacerta aurelioi*, *Iberolacerta bonnali* and *Iberolacerta monticola* within the reptiles. However, this does not mean that these are the most vulnerable species to extinction, because this evaluation is only based on vulnerability to climate change, and does not account for other threats or the interaction of climate change with other threats (Brook *et al.*, 2008). Particularly, climate change is likely to induce further habitat changes and fragmentation (due to shifts in plant species distribution and an increase in fire incidence) and the spread of agents of infectious diseases such as the chytridiomycete fungus which is already across the Iberian Peninsula (Garner *et al.*, 2005). These factors are already considered the primary threats to amphibians and reptiles, along with pollution, invasive species, road kills and genetic depression.

For Review Only

From vulnerability to conservation actions

Recommendations to address climate change impacts on biodiversity include a wide variety of measures, with the most popular being monitoring species (with emphasis on the physiological, behavioural and demographic response), restoring habitats and system dynamics, expanding reserve networks, performing assisted dispersal Hoegh-Guldberg *et al.* (2009), reducing other threats and increasing connectivity between suitable habitats (Heller *et al.*, 2009, Lawler, 2009). Probably the most important questions for management are whether species will be able to adapt to future climate conditions without the need to disperse or, if not, if they will be able to disperse. Because these questions are difficult to answer with current knowledge, novel management tools that promote flexible decision-making are emerging, such as adaptative management (Kareiva *et al.*, 2008). Following this methodology, we recommend that monitoring should be directed at the most vulnerable species identified by our research. To infer species-specific conservation measures, the monitoring parameters should include: a) physiological changes in thermal tolerances; b) phenological adjustments, such as changes in aestivation and hibernation periods along the year; c) behavioural thermoregulation changes, such as burrowing or adjustments in daily activity periods; d) quantification of dispersal rates; e) changes in population parameters, such as abundance, fertility and mortality f) incidence of infectious diseases and g) species interactions.

If species are not able to disperse, then management measures will be needed in order to assist local adaptation. Habitat restoration has been proposed as a proactive measure to enhance amphibian resilience to climate change. In particular, a denser network of ponds and water tanks has been recommended for amphibians (Blaustein *et al.*, 2001) in Mediterranean areas. This measure, along with a careful control of river flow and water quality may increase

For Review Only

the probability of amphibians to find suitable habitats during climate warming. Availability of freshwater habitats will be particularly important in the regions predicted to have high species loss, the northern Iberian Peninsula and main mountain systems, but also in extreme southern regions (Beja *et al.*, 2003).

Assisted colonisation has been suggested, as a measure to assist climate change adaptation (Mueller *et al.*, 2008; Cheddadi *et al.*, 2009). This triggered intense debate (McLachlan *et al.*, 2007) because translocation of species originated catastrophic impacts in many existing cases. However, assisted dispersal is particularly relevant for amphibians and reptiles due to their low dispersal ability, and therefore we cannot disregard this management possibility under an extreme probability of extinction scenario. However, we agree with (Hoegh-Guldberg *et al.*, 2008) in that assisted dispersal should only be considered for a given species if at least one of a set of assumptions is met, namely: a) the species should be in immediate risk of extinction; b) species should have low dispersal ability and c) the species range should be highly fragmented. Moreover, those authors suggest that translocations should only be undertaken within biogeographic regions, *i.e.*, regions that share similar species composition, and an assessment of translocation risks should be performed previously, including ecological and socio-economical risks. Translocation risk should subsequently be balanced against those of extinction and safeguarded by detailed scientific understanding.

Protected areas have long been considered one of the most effective tools to conserve biodiversity (Rodrigues *et al.*, 2004), but their effectiveness in securing species under rapid climate change is uncertain (Araújo *et al.*, 2004). However they contribute to minimising threats such as, habitat destruction and fragmentation, road kills and pollution, which ultimately may assist to protect species threatened by climate warming. Therefore, it is important to evaluate if present protected areas would be effective in securing species given their predicted range shifts and whereas there is habitat connectivity between current and

For Review Only

future species distributions. This could be achieved using reserve selection algorithms (*e.g.* Moilanen, 2009), which allow the identification the minimum set of areas necessary to represent all species at a given target. Ultimately, the ability of species to adapt to climate change within nature reserves will depend on the management actions undertaken in each of them. Reserve selection algorithms may also assist in identifying areas within nature reserves where the return of the management investment will be greater for a higher number of species.

If species are able to disperse to new habitats, than management actions will be needed to facilitate dispersal, including the increase of habitat connectivity, in particular of freshwater habitats.

Finally, biodiversity conservation can only be successful under climate change scenarios if socio-economical and environmental policies are integrated and if governments cooperate. Although climate change is a global issue, there is a tendency for actions to be taken by governments individually or by local administration, even with a common European environmental policy. It is recommended that the Portuguese and the Spanish governments embark on joint efforts to conserve Iberian biodiversity, particularly Iberian endemics.

For Review Only

Acknowledgements

SC was supported by a PhD grant (SFRH/BD/21896/2005) and JCB has a contract (Programme Ciência 2007), both from Fundação para a Ciência e Tecnologia. HPP was supported by Australian Research Council grants and an Australian Federal Government Commonwealth Environmental Research Facility grant. We would like to thank Doctor Wilfried Thuiller for assisting with BIOMOD procedures and Madeleine C. Bottrill and the anonymous reviewers for useful comments on early versions of this manuscript.

References

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

Araújo MB, New M (2007) Ensemble forecasting of species distributions. *Trends in Ecology and Evolution,* **22**, 42-47.

Araújo MB, Thuiller W, Pearson RG (2006) Climate warming and the decline of amphibians and reptiles in Europe. *Journal of Biogeography,* **33**, 1712 - 1728.

Beaumont LJ, Hughes L, Pitman AJ (2008) Why is the choice of future climate scenarios for species distribution modelling important? *Ecology Letters,* **11**, 1135 - 1146.

Beja P, Alcazar R (2003) Conservation of Mediterranean temporary ponds under agricultural intensification: an evaluation using amphibians. *Biological Conservation,* **114**, 317-326.

Blaustein AR, Belden LK, Olson DH, Green DM, Root TL, Kiesecker JM (2001) Amphibian breeding and climate change. *Conservation Biology,* **15**, 1804-1809.

Bosch J, Carrascal LM, Durán L, Walker S, Fisher MC (2007) Climate change and outbreaks of amphibian chytridiomycosis in a montane area of Central Spain; is there a link? *Proceedings of the Royal Society B: Biological Sciences,* **274**, 253-260.

Bradshaw WE, Holzapfel CM (2006) Evolutionary Response to Rapid Climate Change. *Science,* **312**, 477-1478.

Brook BW, Sodhi NS, Bradshaw CJA (2008) Synergies among extinction drivers under global change. *Trends in Ecology & Evolution,* **23**, 453-460.

Calosi P, Bilton DT, Spicer JI (2008) Thermal tolerance, acclimatory capacity and vulnerability to global climate change. *Biology Letters,* **4**, 99-102.

For Review Only

Carey C, Alexander MA (2003) Climate change and amphibian declines: is there a link? *Diversity and Distributions,* **9**, 111 - 121.

Cheddadi R, Fady B, François L, Hajar L, Suc J-P, Huang K, Demarteau M, Vendramin GG, Ortu E (2009) Putative glacial refugia of *Cedrus atlantica* deduced from Quaternary pollen records and modern genetic diversity. *Journal of Biogeography*, **36**, 1361 - 1371.

Chadwick EA, Slater FM, Ormerod SJ (2006) Inter- and intraspecific differences in climatically mediated phenological change in coexisting *Triturus* species. *Global Change Biology,* **12**, 1069 - 1078.

Carretero, M.A., Ayllón, E. & Llorente, G. (eds) (2009) *Lista patrón de los anfibios y reptiles de España*. Asociación Herpetológica Española, Barcelona.

European Environmental Agency (2004) *Impacts of Europe's changing climate - An indicator-based assessment.* European Environmental Agency, Luxembourg: Office for Official Publications of the European Communities, 107pp.

Elith J, Graham CH, Anderson RP*, et al.* (2006) Novel methods improve prediction of species' distributions from occurrence data. *Ecography,* **29**, 129-151.

Fielding AH, Bell JF (1997) A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation,* **24**, 38-49.

Garner TWJ, Walker S, Bosch J, Hyatt AD, Cunningham AA, Fisher MC (2005) Widespread European distribution of a global amphibian pathogen. *Emerging Infenctious diseases,* **11**, 1639–1641.

Garzón MB, Dios RS, Ollero HS (2008) Effects of climate change on the distribution of Iberian tree species. *Applied Vegetation Science,* **11**, 169–178.

Gibbons JW, Scott DE, Ryan TJ*, et al.* (2000) The Global Decline of Reptiles, Déjà Vu Amphibians. *BioScience,* **50**, 653-666.

For Review Only

Gómez A, Lunt DH (2006) Refugia within refugia: patterns of phylogeographic concordance in the Iberian Peninsula. In *Phylogeography of Southern European Refugia* (eds Weiss S, Ferrand N), pp. 155-188. Springer, Netherlands.

Harte J, Ostling A, Green JL, Kinzig A (2004) Biodiversity conservation: Climate change and extinction risk. *Nature,* **430**.

Hawkins BA, Diniz-Filho JAF, Jaramillo CA, Soeller SA (2007) Climate, Niche Conservatism, and the Global Bird Diversity Gradient. *The American naturalist,* **170**, S16–S27.

Heller NE, Zavaleta ES (2009) Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation,* **142**, 14-32.

Hewitt GM (1996) Some genetic consequences of ice ages, and their role in divergence and speciation. *Biological Journal of the Linnean Society,* **58**, 247–276.

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology,* **25**, 1965-1978.

Hoegh-Guldberg O, Hughes L, McIntyre S, Lindenmayer DB, Parmesan C, Possingham HP, Thomas CD (2008) Assisted Colonization and Rapid Climate Change. *Science,* **321**, 345 - 346.

Hughes L (2000) Biological consequences of global warming: is the signal already apparent? *Trends in Ecology & Evolution,* **15**, 56-61.

IPCC (2007) *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Switzerland, 104pp.

IPCC-TGICA (2007) General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment. Version 2. Prepared by T.R. Carter on behalf of the

For Review Only

Intergovernmental Panel on Climate Change, Task Group on Data and Scenario Support for Impact and Climate Assessment.

Isaac JL, Vanderwal J, Williams SE, Johnson CN (2008) Resistance and resilience: quantifying relative extinction risk in a diverse assemblage of Australian tropical rainforest vertebrates. *Diversity and Distributions,* **15**, 280-288.

Kareiva P, C., Enquist C, Johnson A*, et al.* (2008) Synthesis and Conclusions. In *Preliminary review of adaptation options for climate-sensitive ecosystems and resources. Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research.* (eds Julius SH, J.M. West), pp. 66. U.S. Environmental Protection Agency. Washington, DC.

Kearney M, Porter W (2009) Mechanistic niche modelling: combining physiological and spatial data to predict species' ranges. Ecology Letters, 2009, 334-350.

Keith DA, Akçakaya HR, Thuiller W*, et al.* (2008) Predicting extinction risks under climate change: coupling stochastic population models with dynamic bioclimatic habitat models. *Biology Letters,* **4**, 560-563.

Lawler JJ (2009) Climate Change Adaptation Strategies for Resource Management and Conservation Planning. *Annals of the New York Academy of Sciences,* **1162**, 79-98.

Liu C, Berry PM, Dawson TP, Pearson RG (2005) Selecting thresholds of occurrence in the prediction of species distributions. *Ecography,* **28**, 385-393.

Loureiro A, Ferrand de Almeida N, Carretero MA, Paulo OS (Eds.) (2008) *Atlas dos Anfíbios e Répteis de Portugal,* Instituto da Conservação da Natureza e da Biodiversidade, Lisboa.

Malcolm JR, Liu C, Neilson RP, Hansen L, Hannah L (2006) Global warming and extinctions of endemic species from biodiversity hotspots. *Conservation Biology,* **20**, 538-548.

For Review Only

Marmion M, Parviainen M, Luoto M, Heikkinen RK, Thuiller W (2009) Evaluation of consensus methods in predictive species distribution modelling. *Diversity and Distributions,* **15**, 59-69.

Massot M, Clobert J, Ferrière R (2008) Climate warming, dispersal inhibition and extinction risk. *Global Change Biology,* **14**, 461-469.

McCarty JP (2002) Ecological Consequences of Recent Climate Change. *Conservation Biology,* **15**, 320 - 331.

McLachlan JS, Hellmann JJ, Schwartz MW (2007) A framework for debate of assisted migration in an era of climate change. *Conservation Biology,* **21**, 297-302.

Médail F, Quézel P (1999) Biodiversity hotspots in the Mediterranean Basin: Setting Global Conservation Priorities. *Conservation Biology,* **6**, 1510 - 1513.

MIO-ECSDE (2003) Climate change and the Mediterranean. *Sustainable Mediterranean,* **32**, 1-24.

Mittermeier RA, Gil PR, Hoffman M, et al. (2005) *Hotspots Revisited: Earth's Biologically Richest and Most Endangered Terrestrial Ecoregions*. University of Chicago Press, 392 pp.

Moilanen A, Wilson KA, Possingham H (Eds.) (2009) *Spatial Conservation Prioritization. Quantitative Methods and Computational Tools* Oxford University Press.

Mueller JM, Hellmann JJ (2008) An Assessment of Invasion Risk from Assisted Migration. *Conservation Biology,* **22**, 562 - 567.

Myers N, Mittermeler RA, Mittermeler CG, da Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. *Nature,* **403**, 853-858.

Parmesan C (2006) Ecological and Evolutionary Responses to Recent Climate Change. *Annual review of ecology, evolution, and systematics,* **37**, 637-669.

Parmesan C (2007) Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Global Change Biology,* **13**, 1860-1872.

For Review Only

Pearson RG, Dawson TP (2003) Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography,* **12**, 361-371.

Pearson RG, Thuiller W, Araújo MB*, et al.* (2006) Model-based uncertainty in species range prediction. *Journal of Biogeography,* **33**, 1704-1711.

Phillips SJ, Anderson RP, Schapire RE (2006) Maximum entropy modeling of species geographic distributions. *Ecological Modelling,* **190**, 231-259.

Phillips SJ, Dudik M (2008) Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography,* **31**, 161-175.

Phillips SJ, Dudík M, Schapire RE (2004) A Maximum Entropy Approach to Species Distribution Modeling. *Proceedings of the Twenty-First International Conference on Machine Learning*, 655-662.

Pinho C, Harris DJ, Ferrand N (2007) Comparing patterns of nuclear and mitochondrial divergence in a cryptic species complex: the case of Iberian and North African wall lizards (*Podarcis*, Lacertidae). *Biological Journal of the Linnean Society,* **91**, 121–133.

Pleguezuelos JM, Márquez R, Lizana M (2002) *Atlas y Libro Rojo de los Anfíbios y Reptiles de España.* Dirección General de Conservación de la Naturaleza - Asociación Herpetologica Española: Madrid.

Pounds JA, Bustamante MR, Coloma LA*, et al.* (2006) Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature,* **439**, 161-167.

R Development Core Team (2008). *R: A language and environment for statistical computing*. Foundation for Statistical Computing, Vienna, Austria.

Rodrigues ASL, Andelman SJ, Bakarr MI*, et al.* (2004) Effectiveness of the global protected area network in representing species diversity. *Nature,* **428**, 640-643.

For Review Only

Root TL, MacMynowski DP, Mastrandrea MD, Schneider SH (2005) Human-modified temperatures induce species changes: Joint attribution. *Proceedings of the National Academy of Science,* **102**, 7465-7469.

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. *Nature,* **421**, 57-60.

Sala OE, Chapin FS, Armesto JJ, *et al.* (2000) Global Biodiversity Scenarios for the Year 2100. *Science,* **287**, 1770 - 1774.

Seo C, Thorne JH, Hannah L, Thuiller W (2009) Scale effects in species distribution models: implications for conservation planning under climate change. *Biology Letters,* **5**, 39-43.

Skelly DK, Joseph LN, Possingham HP, Freidenburg LK, Farrugia TJ, Kinnison MT, Hendry AP (2007) Evolutionary responses to climate change. *Conservation Biology,* **21**, 1353-1355.

Spector S (2002) Biogeographic crossroads as priority areas for biodiversity conservation. *Conservation Biology,* **16**, 1480-1487.

Thomas CD, Cameron A, Green RE, *et al.* (2004) Extinction risk from climate change. *Nature,* **427**, 145-148.

Thuiller W (2004) Patterns and uncertainties of species' range shifts under climate change. *Global Change Biology,* **10**, 2020 - 2027.

Thuiller W, Albert C, Araújo MB, *et al.* (2008) Predicting global change impacts on plant species' distributions: Future challenges. *Perspectives in plant ecology, evolution and systematics,* **9**, 137–152.

Thuiller W, Lafourcade B, Engler R, Araujo MB (2009) BIOMOD - a platform for ensemble forecasting of species distributions. *Ecography,* **32**, 369-373.

For Review Only

Thuiller W, Lavorel S, Araújo MB, Sykes MT, Prentice IC (2005) Climate change threats to plant diversity in Europe. *Proceedings of the National Academy of Sciences of the United States of America,* **102**, 8245-8250.

Wake DB (2007) Climate change implicated in amphibian and lizard declines. *PNAS,* **104**, 8201-8202.

Walther G-R, Post E, Convey P, *et al.* (2002) Ecological responses to recent climate change. *Nature,* **416**, 389-395.

Webster M, Forest C, Reilly J, *et al.* (2002) In *MIT Joint Program on the Science and Policy of Global Change - report nº 95*, pp. 23.

Williams SE, Shoo LP, Isaac JL, Hoffmann AA, Langham G (2008) Towards an Integrated Framework for Assessing the Vulnerability of Species to Climate Change. *PLOS BIOLOGY,* **6**, 2621-2626.

Zweig MH, Campbell G (1993) Receiver-Operating Characteristic (ROC) plots: a fundamental evaluation tool in clinical medicine. *Clinical Chemistry,* **39**, 561-577.

For Review Only

Table 1 – Amphibian species list, conservation status under IUCN criteria (NE – not evaluated, LC – least concern, NT – near threatened, VU – vulnerable, EN – endangered), number of grid cells where each species is currently predicted to occur (current), number of grid cells where habitat is predicted to become unsuitable (negative values) or become suitable (positive values) in the future and overall tendency under storylines A2 and B2 and unlimited dispersal assumption. * indicates species strictly endemic to the Iberian Peninsula.

Species	IUCN	Current	2020	2050	2080	Tendency	2020	2050	2080	Tendency
*Alytes cisternasii**	NT	2123	2460	-1263	-2114	Expansion/ Contraction	1496	760	-1164	Expansion/ Contraction
*Alytes dickhilleni**	VU	415	-415	-414	-415	Contraction	-415	-415	-415	Contraction
*Calotriton asper***	NT	385	-200	-384	-385	Contraction	-173	-316	-385	Contraction
*Chioglossa lusitanica**	VU	790	-727	-750	-788	Contraction	-790	-734	-774	Contraction
*Discoglossus galganoi**	NT	2472	-2286	-2472	-2472	Contraction	-2337	-2428	-2416	Contraction
*Discoglossus jeanneae**	NT	1474	1991	3922	4684	Expansion	2805	2439	5052	Expansion
*Lissotriton boscai**	LC	2371	3571	-40	-1776	Expansion/ Contraction	3148	1177	553	Expansion
Pelobates cultripes	NT	3087	3988	4232	3936	Expansion	3998	4097	3933	Expansion
*Pelodytes ibericus**	LC	927	-2	487	-648	Contraction/ Expansion/Contaction	86	228	210	Expansion
Pelophylax perezi	LC	5607	-864	-47	-1849	Contraction	-617	-752	-526	Contraction
Pleurodeles waltl	NT	2826	-689	-1751	-284	Contraction	-974	-1710	1	Contraction
*Rana iberica**	VU	1324	-370	-1115	-1324	Contraction	-673	-946	-1132	Contraction
*Rana pyrenaica***	VU	89	-89	-89	-89	Contraction	-89	-89	-89	Contraction
Triturus marmoratus	LC	2080	-2075	-2080	-2080	Contraction	-2080	-2080	-2080	Contraction
*Triturus pygmaeus**	NT	1358	1277	1849	1585	Expansion	1649	1674	1849	Expansion

For Review Only

Table 2 – Reptile species list, conservation status under IUCN criteria (NE – not evaluated, LC – least concern, NT – near threatened, VU – vulnerable, EN – endangered), number of grid cells where each species is currently predicted to occur (current), number of grid cells where habitat is predicted to become unsuitable (negative values) or become suitable (positive values) in the future and overall tendency under storylines A2 and B2 and unlimited dispersal assumption. * indicates species strictly endemic to the Iberian Peninsula.** indicates species endemic to the Pyrenean Mountains.

Species	IUCN	Current	2020	2050	2080	Tendency	2020	2050	2080	Tendency
Acanthodactylus erythrurus	NT	2545	4004	4354	4627	Expansion	3753	4065	4341	Expansion
*Algyroides marchi**	VU	204	-155	292	305	Contraction/ Expansion	49	257	-65	Expansion/ Contraction
*Blanus cinereus**	LC	2778	1725	2152	2398	Contraction	1787	1620	2416	Expansion
*Chalcides bedriagai**	NT	2344	2891	3553	3510	Expansion	2432	2679	4110	Expansion
Chalcides striatus	LC	2937	1108	-263	-249	Expansion/ Contraction	714	-702	741	Expansion
Coronella girondica	LC	2899	4606	2082	4572	Expansion	2484	2432	4689	Expansion
Hemorrhois hippocrepis	LC	2583	1313	2325	2326	Expansion	1275	1962	2720	Expansion
*Iberolacerta aranica***	CR	23	-23	-23	-23	Contraction	-23	-23	-23	Contraction
*Iberolacerta aurelioi**	EN	19	-19	-19	-19	Contraction	-19	-19	-19	Contraction
*Iberolacerta bonnali***	VU	64	-64	-64	-64	Contraction	-64	-64	-64	Contraction
*Iberolacerta cyreni**	EN	867	-427	-588	-750	Contraction	-426	-538	-742	Contraction
*Iberolacerta monticola**	VU	524	-469	-524	-524	Contraction	-524	-524	-524	Contraction
*Lacerta schreiberi**	NT	1560	778	-367	-875	Expansion/ Contraction	-95	-54	-401	Contraction
*Podarcis bocagei**	LC	807	-761	-806	-807	Contraction	-807	-807	-806	Contraction
*Podarcis carbonelli**	VU	519	212	-226	-499	Expansion/ Contraction	209	-193	-7	Expansion/ Contraction
Podarcis hispanica	LC	4522	2233	2367	2926	Expansion	2235	2294	3033	Expansion
Psammodromus algirus	LC	4311	2643	1170	-1220	Expansion/ Contraction	1842	1349	1470	Expansion
Psammodromus hispanicus	LC	2882	1705	2403	2524	Expansion	1959	2416	3736	Expansion
Rhinechis scalaris	LC	2674	4742	4915	4927	Expansion	4832	4911	4922	Expansion
Timon lepida	LC	4080	-1325	-1219	-1950	Contraction	-1974	-1310	-20	Contraction

For Review Only

Vipera latastei	VU	2688	3865	3873	3630	Expansion	3344	3890	3139	Expansion
*Vipera seoanei**	EN	873	-867	-873	-873	Contraction	-873	-873	-873	Contraction

For Review Only

Table 3 – Species predicted to completely lose distribution range in the Iberian Peninsula until each of the periods (2020, 2050 and 2080) according to storylines (A2, B2 or both) and under the unlimited dispersal scenario. * indicates species strictly endemic to the Iberian Peninsula.** indicates species endemic to the Pyrenean Mountains.

Species	**2020**	**2050**	**2080**
*Alytes dickhilleni**	A2/B2	B2	A2/B2
*Calotriton asper***	-	A2	A2/B2
*Chioglossa lusitanica**	B2	-	-
*Discoglossus galganoi***	-	-	A2
*Iberolacerta aranica***	A2/B2	A2/B2	A2/B2
*Iberolacerta aurelioi**	A2/B2	A2/B2	A2/B2
*Iberolacerta bonnali***	A2/B2	A2/B2	A2/B2
*Iberolacerta monticola**	B2	A2/B2	A2/B2
*Podarcis bocagei**	B2	B2	A2
*Rana iberica**	-	-	A2
*Rana pyrenaica***	A2/B2	A2/B2	A2/B2
Triturus marmoratus	B2	A2/B2	A2/B2
*Vipera seoanei**	B2	A2/B2	A2/B2

For Review Only

Appendix A.1 –Maximum (Max), Minimum (Min) and standard deviation (STDV), of the number of occurrences predicted for each amphibian species in each year and in each storyline, within the 9 modelling methods and the 3 global circulation models.

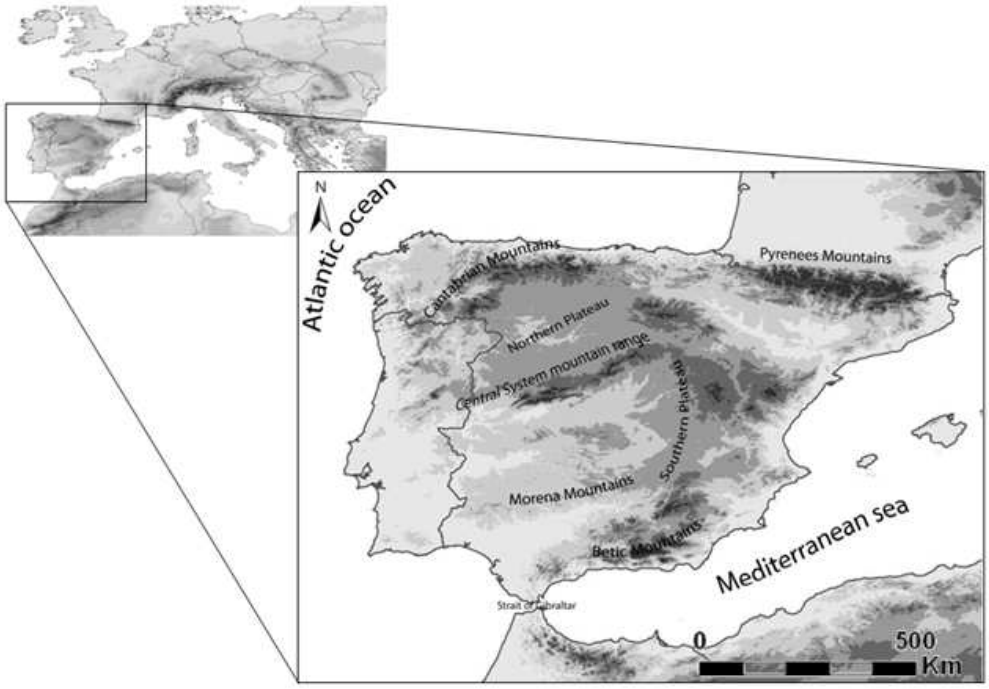
	2020						2050						2080					
	A2			B2			A2			B2			A2			B2		
Species	**Max**	**Min**	**STDV**	**Max**	**Min**	**STDV**	**Max**	**Min**	**STDV**	**Max**	**Min**	**STDV**	**Max**	**Min**	**STDV**	**Max**	**Min**	**STDV**
Alytes cisternasii	7293	71	2242.1	7535	34	2370.0	7207	2	2740.5	7023	8	2479.8	7602	0	2647.8	7602	0	2653.5
Alytes dickhilleni	5358	0	1406.3	5822	0	1795.8	5529	0	1792.7	5598	0	1695.5	7602	0	2315.4	7602	0	2305.5
Calotriton asper	7599	0	2858.6	7600	0	1755.6	4292	0	1090.9	7581	27	2156.2	7434	0	2258.4	7587	0	2203.3
Chioglossa lusitanica	1064	0	350.9	886	0	295.2	1584	0	391.5	7385	0	1393.2	3156	0	709.1	2428	0	524.7
Discoglossus galganoi	7420	0	2234.4	6310	0	1748.5	4614	0	1809.2	4777	0	1737.1	7602	0	2906.3	7602	0	2683.6
Discoglossus jeanneae	7602	228	2569.2	7602	374	2461.3	7602	776	2443.3	7602	749	2360.1	7602	197	3010.9	7602	710	2608.1
Lissotriton boscai	7595	1076	2196.3	7345	167	2069.3	7199	31	2082.1	7212	490	1917.1	7602	0	2607.7	7602	0	2444.6
Pelobates cultripes	7602	52	2273.2	7602	162	2235.3	7569	148	2406.4	7521	122	2220.9	7602	0	2709.4	7602	0	2592.4
Pelodytes ibericus	7387	13	2051.0	7584	268	2059.7	7516	509	2088.5	6857	22	1866.0	7519	0	2373.3	7328	0	2256.2
Pelophylax perezi	7601	372	2572.3	7602	347	2523.7	7602	315	2561.0	7602	311	2424.0	7602	0	2789.7	7602	0	2794.3
Pleurodeles waltl	7170	7	2255.1	7552	291	2124.8	7308	73	1997.5	7391	154	1912.2	7602	0	2568.5	7602	212	2544.5
Rana iberica	4186	7	1271.4	7511	0	1873.9	7413	0	1834.1	7503	0	2230.5	7515	0	2163.2	7544	0	2186.6
Rana pyrenaica	7487	0	2225.4	7389	0	1954.3	7466	0	2385.7	7590	0	2394.7	7548	0	2077.4	7490	0	2383.3
Triturus marmoratus	4589	0	1458.7	6450	0	1729.7	7313	0	1841.9	3889	0	1193.0	4473	0	1266.2	4179	0	1244.7
Triturus pygmaeus	7602	248	2386.1	7590	651	2141.6	7106	133	2218.2	7034	90	2155.6	7602	0	2720.7	7602	406	2336.6

For Review Only

Appendix A.2 –Maximum (Max), minimum (Min), and standard deviation (STDV), of the number of occurrences predicted for each reptile species in each year and in each storyline, within the 9 modelling methods and the 3 global circulation models.

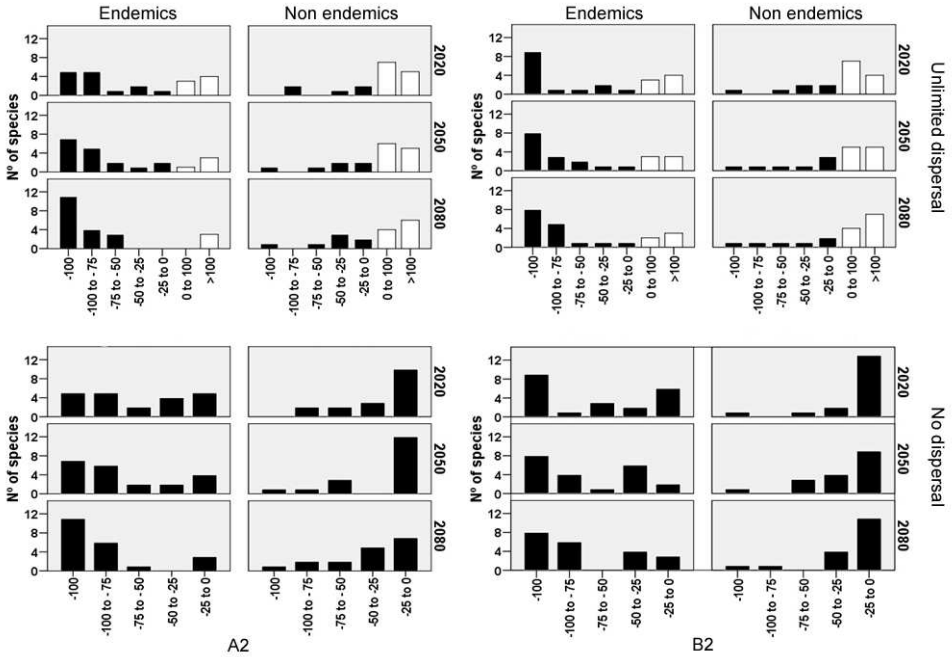
	2020						2050						2080					
	A2			B2			A2			B2			A2			B2		
Species	**Max**	**Min**	**STDV**	**Max**	**Min**	**STDV**	**Max**	**Min**	**STDV**	**Max**	**Min**	**STDV**	**Max**	**Min**	**STDV**	**Max**	**Min**	**STDV**
Blanus cinereus	7322	591	1676.3	7524	636	1693.2	7369	850	1707.5	6521	374	1691.0	7602	34	2593.4	7602	73	2157.2
Chalcides bedriagai	7598	53	2481.0	7148	268	2297.7	7409	299	2470.3	7376	111	2394.4	7602	20	3096.2	7602	63	2818.1
Chalcides striatus	7602	328	2238.7	7466	47	2164.6	7509	157	2316.2	7307	396	2121.2	7602	59	2565.4	7602	515	2502.4
Coronella girondica	7602	182	2662.8	7602	52	2788.2	7602	157	2599.1	7602	262	2676.9	7602	74	2992.2	7602	130	2815.2
Hemorrhois hippocrepis	6982	1380	1545.2	6359	902	1468.2	7281	1241	1835.1	7121	1208	1719.0	7602	0	2510.3	7602	0	2137.0
Iberolacerta aranica	463	0	122.1	2553	0	489.7	122	0	28.3	7493	0	1441.0	7600	0	1461.8	7592	0	1458.5
Iberolacerta aurelioi	7456	0	2368.1	7527	0	2390.1	7531	0	2401.9	7527	0	2377.6	7586	0	2414.6	7533	0	2400.6
Iberolacerta bonnali	7543	0	2406.0	7570	0	2413.6	7579	0	2420.1	7573	0	2402.6	7567	0	1459.5	7577	0	2418.1
Iberolacerta cyreni	7598	0	2327.3	7598	9	2324.0	7598	0	2320.5	7597	0	2343.6	7582	0	2331.2	7596	0	2393.4
Iberolacerta monticola	7510	0	2059.9	7446	0	1973.2	5825	0	1154.0	5002	0	982.8	6755	0	2171.6	6166	0	1612.7
Lacerta schreiberi	7378	361	2302.8	7235	0	2509.0	7325	0	2491.8	7291	58	2565.3	7602	0	2564.4	7313	0	2553.4
Podarcis bocagei	1609	0	527.1	1880	0	545.7	1786	0	561.8	1289	0	474.5	7602	0	1515.4	7602	0	1938.3
Podarcis carbonelli	7522	152	2816.1	7524	15	2654.5	7487	45	2465.4	6223	43	2142.9	7602	0	2742.7	7602	0	2703.4
Podarcis hispanica	7602	380	2543.7	7602	79	2739.4	7602	565	2756.7	7602	351	2626.6	7602	0	3080.0	7602	0	2922.5
Psammodromus algirus	7602	140	2737.2	7602	317	2747.0	7602	178	2833.4	7602	383	2740.9	7602	0	3224.3	7602	0	2889.7
Psammodromus hispanicus	7417	274	2760.3	7072	164	2697.7	7439	231	2974.2	7434	271	2867.7	7602	0	3164.2	7602	0	3026.3
Rhinechis scalaris	7602	372	2233.7	7602	82	2419.2	7602	1275	2299.2	7602	1538	2096.5	7602	0	2596.5	7602	0	2587.9
Timon lepida	7602	237	2466.0	7602	82	2709.5	7602	255	2772.4	7602	591	2616.2	7602	0	3121.7	7602	0	3022.9
Vipera latastei	7594	63	2148.9	6928	71	2270.8	7222	198	2178.5	7244	556	1811.9	7570	0	2997.2	7232	0	2838.1
Vipera seoanei	3144	0	643.7	949	0	265.2	3314	0	656.8	967	0	291.6	4931	0	967.9	4811	0	940.0

For Review Only

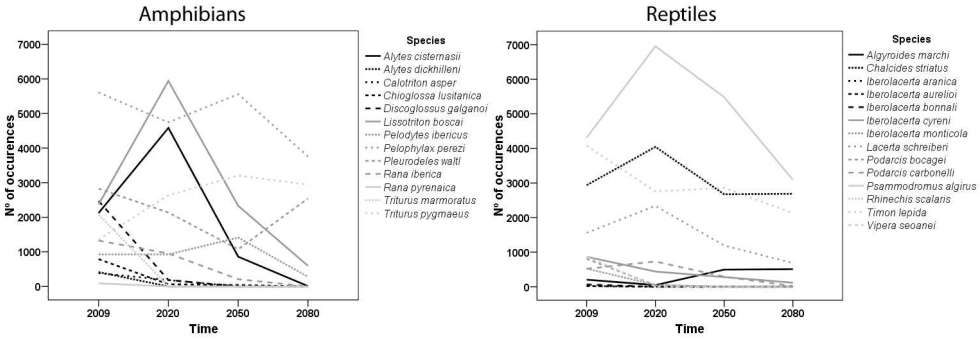


Location and map of the Iberian Peninsula depicting altitude and major geographic features. Altitude is represented in a range of grey colours where darker areas represent higher altitude.
168x123mm (96 x 96 DPI)

For Review Only

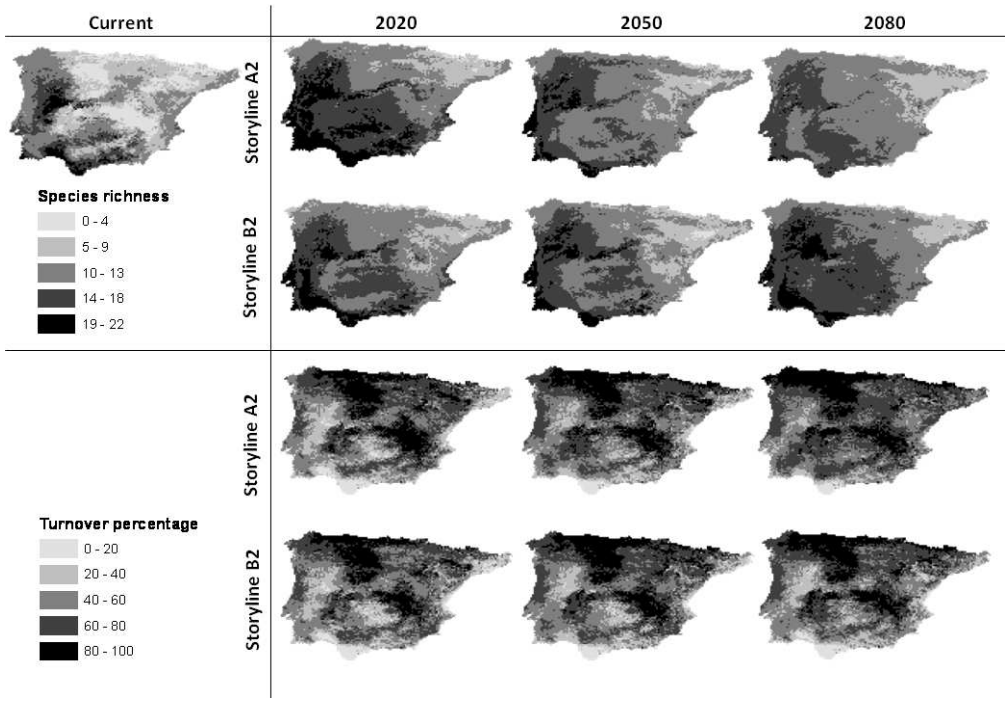


Number of species predicted to gain or lose suitable habitat under different dispersion assumptions (unlimited dispersal and no dispersal) and storylines (A2 and B2), categorised by the percentage of range contraction or expansion relatively to present (x axis). Endemics and non endemics species are represented separately, with endemics representing species strictly endemic to the Iberian Peninsula and species endemic to the Pyrenean Mountains. Black columns represent species predicted to lose suitable habitat while white columns represent species predicted to gain suitable habitat.
275x190mm (96 x 96 DPI)



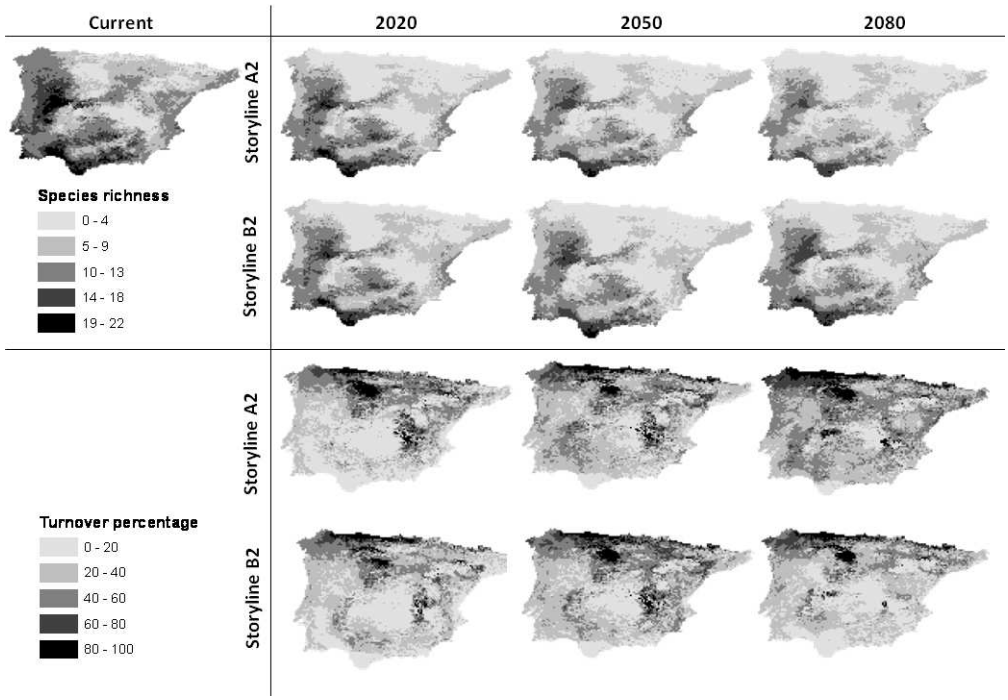
Variation in the predicted number of occurrences through time for species predicted to lose suitable habitat according to the unlimited dispersion scenario and storyline A2.
132x47mm (300 x 300 DPI)

Review Only



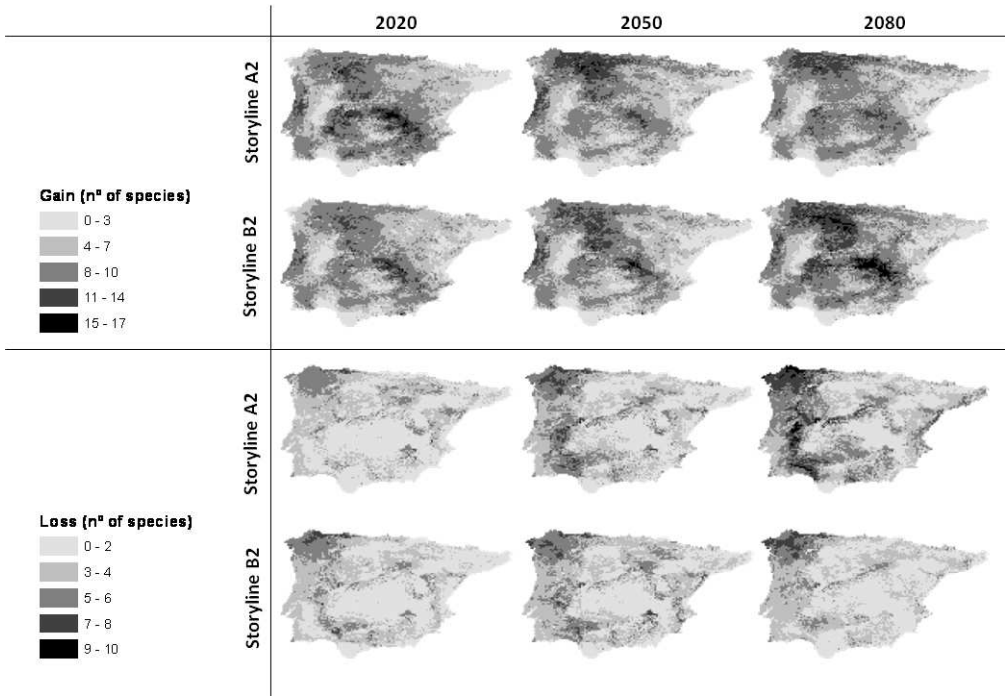
Spatial distribution of predicted current and future (2020, 2050 and 2080) species richness and turnover percentage according to storylines A2 and B2 and under the unlimited dispersion scenario.
275x190mm (96 x 96 DPI)

For Review Only



Spatial distribution of predicted current and future (2020, 2050 and 2080) species richness and turnover percentage according to storylines A2 and B2 and under the no dispersion scenario.
275x190mm (96 x 96 DPI)

For Review Only



Spatial distribution of predicted gain (under the unlimited dispersion scenario) and loss (in both dispersion scenarios) of number of species in the future (2020, 2050 and 2080) according to storylines A2 and B2 and under the unlimited dispersion scenario.
275x190mm (96 x 96 DPI)

For Peer Review Only