

1 **Hot and bothered: using trait-based approaches to assess climate change vulnerability in**  
2 **reptiles**

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20 **Abstract**

21 One-fifth of the world's reptiles are currently estimated as threatened with extinction, primarily due to  
22 the immediate threats of habitat loss and overexploitation. Climate change presents an emerging slow-  
23 acting threat. However, few IUCN Red List assessments for reptiles explicitly consider the potential  
24 role of climate change as a threat. Thus, climate change vulnerability assessments can complement  
25 existing Red List assessments and highlight further, emerging priorities for conservation action.

26 Here we present the first trait-based global climate change vulnerability assessment for reptiles to  
27 estimate the climate change vulnerability of a random representative sample of 1498 species of  
28 reptiles. We collected species-specific traits relating to three dimensions of climate change,  
29 sensitivity, low adaptability, and exposure which we combined to assess overall vulnerability.

30 We found 80.5% of species highly sensitive to climate change, primarily due to habitat specialisation,  
31 while 48% had low adaptability and 58% had high exposure. Overall, 22% of species assessed were  
32 highly vulnerable to climate change. Hotspots of climate vulnerability did not always overlap with  
33 hotspots of threatened species richness, with most of the vulnerable species found in northwestern  
34 South America, southwestern USA, Sri Lanka, the Himalayan Arc and southern India. Most families  
35 were found to be significantly more vulnerable to climate change than expected by chance.

36 Our findings build on previous work on reptile extinction risk to provide an overview of the risk  
37 posed to reptiles by climate change. Despite significant data gaps for a number of traits, we  
38 recommend that these findings are integrated into reassessments of species' extinction risk, to monitor  
39 both immediate and slow-acting threats to reptiles.

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41

42 **Keywords:** climate change, exposure, sensitivity, adaptability, IUCN Red List, herpetology

## 43 1. Introduction

44 Latest climate data show that the rate of global surface temperature warming since 1950 continues  
45 unabated, rising between 0.113°C and 0.116°C per decade (Karl et al. 2015). Impacts from climate  
46 change are expected to intensify, with global surface temperature increase likely to exceed 4°C by  
47 2100 if no mitigation measures are put in place (World Bank 2014), presenting a major emerging  
48 threat to biodiversity (Dickinson et al. 2014; Pacifici et al. 2015). Climate change effects on species  
49 include changes to species' ranges, both altitudinal (e.g. Menendez et al. 2014) and latitudinal (e.g.  
50 Hill et al. 2002), habitat associations (e.g. Menendez and Gutierrez 2004), life-history phenology (e.g.  
51 Pearce-Higgins et al. 2015), disease emergence (e.g. Sarmiento et al. 2014), and increased extinction  
52 risk (Carpenter et al. 2008; Dickinson et al. 2014).

53 Frameworks for assessing species' extinction risk, such as the IUCN Red List of Threatened Species  
54 (IUCN 2015b), have been criticised for insufficiently incorporating emerging and often slow-acting  
55 climate change threats (Keith et al. 2014; Thomas et al. 2011). At present, the most commonly  
56 identified threats to species on the IUCN Red List are habitat loss, overexploitation and invasive  
57 species (IUCN 2015b), while only 8% of the 67 000 species assessed under the current criteria system  
58 (IUCN 2001) are recorded as threatened by climate change (IUCN 2015b). The IUCN Red List  
59 Criteria effectively account for climate change in threatened species (Akcakaya et al. 2014; Pearson et  
60 al. 2014), although a number of factors may still prevent the adequate listing of climate change for  
61 threatened species: species may be perceived as susceptible to climate change, but may not yet be  
62 exposed to significant changes, or vice versa (Foden et al. 2013); assessors may approach climate  
63 change threats inconsistently due to uncertainties surrounding current projections of climate change  
64 and their effects on species (Keith et al. 2014; Westoby and Burgman 2006); other threats, acting  
65 synergistically with climate change, may be more easily understood and recorded, thus  
66 underestimating the importance of climate change (Hof et al. 2011).

67 To complement existing frameworks, climate change-specific assessments were developed using a  
68 number of different approaches (Pacifici et al. 2015). With over a million terrestrial species  
69 potentially already 'committed to extinction' by the middle of the century due to climate change  
70 (Keith et al. 2014), climate change vulnerability assessments are of utmost importance to effectively  
71 quantify climate change threats, inform mitigation and adaptation policy and prevent adverse effects  
72 from climate change (Young et al. 2015).

73 Since considerable uncertainty exists surrounding climate change projections and their effects on  
74 species (Tuberville et al. 2015), assessing intrinsic biological traits which predispose species to  
75 climate change risk has more recently emerged as an alternative approach; these are collectively  
76 known as trait-based approaches. These approaches have been used to complement IUCN Red List  
77 extinction risk assessments, providing a supplementary analysis that can be used to inform overall  
78 species risk and identify additional conservation priorities (Foden et al. 2013).

79 Trait-based approaches collate data concerning different 'dimensions' of climate change vulnerability,  
80 typically including species' sensitivity, adaptability, and exposure to climate change (Foden et al.  
81 2013; Pacifici et al. 2015; Still et al. 2015). Trait-based assessments often rank species vulnerability  
82 within the dataset, as many of the trait value thresholds used are arbitrary (Foden et al. 2013; Pacifici  
83 et al. 2015), and are most often expressed as "low" and "high" vulnerability (Carr et al. 2014; Foden  
84 et al. 2013). Comparisons between analyses are therefore difficult (Foden et al. 2013; Pacifici et al.  
85 2015). Despite this shortcoming, trait-based approaches are becoming increasingly common in the  
86 scientific literature (Young et al. 2015), with recent assessments of a range of taxa including birds and  
87 amphibians (e.g.; Carr et al. 2014; Foden et al. 2013; Hagger et al. 2013), mammals (Dickinson et al.  
88 2014), reptiles (e.g.; Carr et al. 2014; Hagger et al. 2013), insects (e.g.; Conti et al. 2014), plants (e.g.;  
89 Still et al. 2015), and corals (Foden et al. 2013). Trait-based approaches have been widely adopted by  
90 conservation planning agencies as a prioritization technique for climate change-affected species  
91 (Dawson et al. 2011; Pacifici et al. 2015; Williams et al. 2008); they can, however, still be constrained  
92 by limited data availability, especially for commonly incorporated traits such as dispersal capacity, for  
93 which few data exist beyond well-studied species (Foden et al. 2013; Pacifici et al. 2015). Although

94 being referred to as ‘trait-based’, traits are often derived indirectly from species’ ranges (e.g. climatic  
95 and environmental factors), rather than being based on species-specific data (e.g. from laboratory  
96 experiments on temperature or water requirements) which are generally sparse.

97 Of the currently 10 272 described reptile species (Uetz & Hošek 2015), around one in five species is  
98 estimated to be threatened with extinction, based on a random sample of 1500 species (Böhm et al.  
99 2013); climate change was only listed as a threat in 9% of threatened terrestrial reptiles compared to  
100 17% of threatened freshwater and marine reptiles. However, the impacts of climate change on reptiles  
101 potentially affect all aspects of their life-history (Meiri et al. 2013). Most reptiles have specific  
102 microhabitat, temperature and moisture requirements for metabolism and reproduction; they are thus  
103 likely to be highly sensitive to climate change (Tuberville et al. 2015). Approximately 85% of reptiles  
104 are oviparous (Tinkle and Gibbons, 1977) and may be affected by increasing temperatures during  
105 development (Hawkes et al. 2009), potentially skewing the sex ratio for species with temperature-  
106 dependent sex determination, reducing hatching success, or shifting breeding season phenology  
107 (Hawkes et al. 2009; López-Luna et al. 2015). Other aspects of reptile life-history affected by climate  
108 change include altered behaviour patterns such as time spent foraging, basking, or resting (Bickford et  
109 al. 2010; Meiri et al. 2013), changes in the use of habitat and resources (Bickford et al. 2010; Scharf et  
110 al. 2014), disease (Sarmiento et al. 2014) and altered habitat structure which may also impact prey  
111 diversity and abundance (Whitfield et al. 2007).

112 Here, we use a trait-based approach (Foden et al. 2013; Carr et al. 2014) to estimate climate change  
113 vulnerability of a random representative sample of 1498 species of reptiles from 70 families, all of  
114 which have been previously assessed as part of the Sampled Red List Index (SRLI) for the IUCN Red  
115 List (Böhm et al. 2013). Specifically, we examine data availability for trait-based climate change  
116 vulnerability assessments, determine taxonomic and geographic variability of climate change  
117 vulnerability, and discuss how climate change vulnerability assessments complement what we have  
118 previously learned about conservation priorities from IUCN Red List assessments.

## 119 **2. Methods**

### 120 *2.1 Species dataset*

121 Our assessment was based on a sample of 1500 reptile species for which IUCN Red List assessments  
122 had previously been carried out as part of the Sampled Red List Index project (Böhm et al. 2013); for  
123 the current assessment, two species were no longer taxonomically valid, resulting in a final total of  
124 1498 species for assessment. For the IUCN Red List assessment by Böhm et al. (2013), species had  
125 been randomly selected from the species list at the start of the assessment (Uetz & Hošek 2015)  
126 following the approach in Baillie et al. (2008). A sample of this size was previously found to produce  
127 a broadly representative picture of extinction risk and trends over time (Baillie et al., 2008), and  
128 spatial patterns derived from such samples were found to be in broad agreement with spatial patterns  
129 derived from comprehensive assessments in both mammals and amphibians (B. Collen, unpublished  
130 data). Of the 1498 species in our assessment, 49 were listed as being threatened by climate change on  
131 the IUCN Red List (with 20 of these in the threatened categories Vulnerable, Endangered or Critically  
132 Endangered). All analyses and spatial data extractions were carried out in R version 3.1.2 (R Core  
133 Team 2014), unless otherwise indicated.

### 134 *2.2 Climate change vulnerability assessment*

135 We closely followed the approach by Foden et al. (2013) and Carr et al. (2014) which assesses three  
136 dimensions of climate change vulnerability: sensitivity, poor adaptability and exposure (Foden et al.  
137 2013; Figure 1). Here, species which are both sensitive to climate change and have low adaptability  
138 are considered ‘biologically susceptible’ to climate change. Biologically susceptible species which are  
139 also highly exposed to climate change are referred to as ‘climate change vulnerable’ species  
140 (represented by the area where the three dimensions overlap; Figure 1). We selected traits for three  
141 trait sets pertaining to sensitivity and two trait sets pertaining to low adaptability, identified as  
142 important factors affecting climate change vulnerability of species by Foden et al. (2013) and Carr et

143 al. (2014) during expert workshops: 1. Specialised habitat and/or microhabitat requirements; 2.  
144 Narrow environmental tolerances or thresholds likely to be exceeded due to climate change; 3.  
145 Dependence on interspecific interactions likely to be disrupted by climate change; 4. Poor dispersal  
146 ability; 5. Low capacity to adapt *in-situ* through genetic micro-evolution. One of the trait groups  
147 assessed by Carr et al. (2014), dependence on environmental triggers likely to be disrupted by climate  
148 change, was not included in our analysis due to a lack of data for reptiles in the literature. Similarly,  
149 few data are available in the literature on intrinsic dispersal capacity, which meant that this trait  
150 had to be excluded from the analysis. Traits and underlying hypotheses on their effect on climate  
151 change vulnerability are summarised in Table 1.

152 Traits were collected from published and grey literature, and information given in the IUCN Red List  
153 of Threatened Species. Environmental tolerances and exposure to climate change were calculated  
154 from distribution maps published on the IUCN Red List, using those parts of the distribution where  
155 species are recorded as 'extant', 'probably extant', 'native' or 'reintroduced' (Joppa et al. 2015).  
156 Distribution maps on the IUCN Red List usually exist in the form of generalised range polygons, thus  
157 potentially including large areas of unoccupied, potentially unsuitable areas; this can make  
158 calculations of climatic requirements and tolerance from these distribution maps unrepresentative  
159 (Foden et al. 2013). To address this, we produced amended distribution maps by excluding areas of  
160 unsuitable habitat from our analyses through removing altitudes at which a species did not occur  
161 (from published literature) and cross-referencing habitat types listed on the IUCN Red List (IUCN  
162 2015a) with the spatially explicit Global Land Cover 2000 habitat types. This consists of 23  
163 categories, including natural and human-transformed habitats and water bodies, at 1x1 km resolution  
164 (<http://www.eea.europa.eu/data-and-maps/data/global-land-cover-250m>; Table S3). Detailed  
165 information on the methods, traits and potential caveats can be found in the Supplementary Materials.

166

### 167 2.3 Sensitivity dimension

168 Sensitivity traits and thresholds are summarised in Table 1. We defined habitat specialisation as the  
169 number of habitat types occupied by a species, according to the IUCN Red List habitat classification  
170 (Table S2). Species were classified as microhabitat specialists if they were recorded as exclusively  
171 dependent or recorded in any of the following microhabitats in their IUCN Red List assessment:  
172 mountain rapids/rivulets, ephemeral pools, bamboo, vines, fallen trees, dead wood, tree hollows, trees  
173 bordering water, riverine or gallery forests, ant hills, dunes, open patches in grassland, rocky areas  
174 and outcrops, cliffs, caves, and small streams as well as freshwater- and forest-dependent species.

175

176 We classed species as restricted to high-altitude habitat if they only occurred above 1000 m. To assess  
177 this, we used data on altitudinal range recorded in IUCN Red List assessments. Any data gaps were  
178 then supplemented with altitudinal data at 10 arcminute resolution (Hijmans et al. 2005), extracted by  
179 overlaying amended species distributions and extracting mean, maximum and minimum altitude for  
180 each species. Any data derived from this spatial data process were assumed to be of lower data quality  
181 than information from IUCN Red List assessments. We assessed species' tolerance to changes in  
182 precipitation and temperature regimes by deriving average absolute deviation (AAD) across amended  
183 species distributions from global temperature and precipitation datasets for the period of 1950-2000 at  
184 10 arcminute resolution (Hijmans et al. 2005). AAD represents a variable of dispersion, essentially  
185 representing tolerance of variability in temperature and precipitation across space and seasons for  
186 each species (Foden et al. 2013). Hence, for a dataset  $\{x_1, x_2, \dots, x_n\}$ , AAD is defined as

$$187 \quad \frac{1}{n} \sum_{i=1}^n |x_i - m(X)|$$

188 where each  $x$  represents a monthly mean for a cell within a species' amended range (Foden et al.  
189 2013).

190 Species with the 25% lowest AAD (i.e. lowest environmental tolerance) were classed as being highly  
191 sensitive. Similar quartile thresholds were also used for other continuous trait variables; while highly  
192 arbitrary, these provide an easy-to-use approach to split a continuous variable into a high/low

193 classification. This approach has also been used in similar assessments (Foden et al. 2013; Carr et al.  
194 2014). For more information, and vulnerability scores based on different thresholds, see the  
195 Supplementary Materials.  
196 Information on sensitivity to changes in fire and flooding regimes and interspecific dependencies was  
197 taken from IUCN Red List assessments, with species classed as ‘high’ sensitivity if it was stated they  
198 were dependent on either of these factors, or were threatened by flooding/drought or natural system  
199 modification resulting from fire and fire suppression. Species for which reliance on temperature-  
200 dependent sex determination was stated in the literature were ranked highly sensitive, although overall  
201 data quality was considered low for this trait due to a lack of information for the majority of species.  
202 Dependence on a narrow range of food types was assessed by collating information on diet from the  
203 literature and categorising this information into 18 dietary categories, reflecting reptile dietary habits  
204 (see Table S4): leaf matter; fruit; seeds; nectar; a single taxonomic group of arthropod; a range of  
205 arthropods; other invertebrates; small mammals  $\leq 300$  mm SVL; large mammals  $> 300$  mm SVL;  
206 adult/sub adult birds; bird eggs/juveniles; adult/juvenile reptiles; reptile eggs; adult amphibians;  
207 amphibian larvae; freshwater fish; faeces; and an ‘other’ category for anything outside of these  
208 parameters. For species consuming a wide range of arthropods, or several named arthropod taxa, both  
209 the single type of arthropod and range of arthropods boxes were checked to indicate a generalist of  
210 arthropod prey. Where data were unavailable, we inferred from close congeners where possible.  
211 Species which were restricted to a single dietary category were classified as being highly sensitive.

212

#### 213 *2.4 Adaptability dimension*

214 Adaptability traits and thresholds are summarised in Table 1. We assessed a species range as having  
215 barriers to dispersal if a species occurred exclusively: on mountaintops; small islands of less than 500  
216 m altitude, thus preventing significant elevational dispersal rather than simple inland movement in  
217 response to climate change; and/or within 10 degrees north/south from edges of land masses, here  
218 termed polar edges. We created spatial data layers from geographic data in ArcGIS for all three  
219 barrier components, using altitudinal data at 10 arcminute resolution (Hijmans et al. 2005).  
220 Mountaintop distributions were defined in ArcGIS 10.3 (ESRI) by defining grid cells across a 2x2  
221 grid cell extent as either above or below the mean altitudinal value (see Supplementary Materials).  
222 Finally, we intersected the resulting data layers with the species distributions. Species solely occurring  
223 within polar edges of land masses and/or with their entire distribution confined to small islands and/or  
224 entirely occurring within cells of above mean altitude were regarded as experiencing geographic  
225 barriers to dispersal.

226 We used maximum longevity of species as a proxy for slow turnover of generations, since in many  
227 cases, generation length has not yet been quantified for species (only 31 species had generation length  
228 estimates in the IUCN Red List; see Figure S5 for correlation between generation length and  
229 longevity estimates). We collected longevity data from the literature, including captive and wild  
230 records. While in some cases, animals in captivity may live longer due to better access to food and  
231 medical treatment, in other cases the specific requirements for survival may be unknown or difficult  
232 to fulfil, thus potentially reducing longevity (Mason 2010). Furthermore, records of captive animals  
233 are often based on animals that were still alive at the time of data collection (Scharf et al. 2014), thus  
234 potentially underestimating longevity. Where data were lacking, we used allometric equations of body  
235 mass and longevity by Scharf et al. (2014) to derive an estimate of longevity. We subsequently  
236 classed species as having low adaptive capacity if they were amongst the 25% longest-lived species.

237 Information on reproductive capacity was collected from the literature (based on clutch/litter size and  
238 number of clutches/litters per year; Böhm et al. 2016). Where data was missing, we inferred  
239 reproductive output from close congeners. The 25% of species with lowest reproductive output  
240 being classed as having low adaptive capacity.

#### 241 *2.5 Exposure dimension*

242 Exposure measurements and thresholds are summarised in Table 1. We collected data on five traits  
243 related to exposure: exposure to sea level rise; changes in mean temperature; temperature variability  
244 change; changes in mean precipitation; and precipitation variability change. Exposure to sea level rise

245 was assessed from IUCN Red List habitat data; species occurring exclusively or near-exclusively (i.e.  
246 in only one additional habitat type) in any of the following habitats were deemed as having high  
247 vulnerability to climate change: mangroves, intertidal salt marshes, coastal freshwater, brackish or  
248 saline lakes and lagoons, marine lakes, coastal caves, intertidal shorelines (including rocks, beaches,  
249 flats and tide pools), sea cliffs, rocky offshore islands, and coastal sand dunes.

250

251 As described in Foden et al. (2013), climate change projections at 10 arcminute resolution (Tabor and  
252 Williams 2010) were based on an ensemble of four General Circulation Models (UKMO HadCM3,  
253 MPIM ECHAM5, CSIRO MK3.5 and GFDL CM2.1), and considering three emissions scenarios (B2,  
254 A1B and A2) for 1975 (mean 1961–1990), 2050 (mean 2041–2060) and 2090 (mean 2081–2100).

255 The different emission scenarios provide us with a mid-range projection (scenario A1B) for changes  
256 from 1975 to 2050 (in main results), as well as upper (scenario A2) and lower (scenario B1) bounds  
257 for projections (in Supplementary Materials). We assessed mean change in temperature as the  
258 absolute difference in the mean between 1975 and 2050, and mean change in precipitation as a ratio:  
259 (absolute [((mean precipitation in 2050) – (mean precipitation in 1975)) / mean precipitation in  
260 1975])). For changes in temperature and precipitation variability, we again estimated AAD between  
261 1975 and 2050.

262

### 263 *2.6 Vulnerability assessment*

264 We aimed to collect data for all selected traits. In some cases, we inferred information on diet and  
265 reproductive output from congeners (see Supplementary Materials). Given the diversity of data  
266 sources and resulting data quality, we also scored data quality (high, medium, low) for all trait data to  
267 evaluate the feasibility and suitability of collating trait data from existing published or open access  
268 sources rather than through consultation with experts at workshops (the latter being the approach  
269 previously used by Carr et al. 2014). This also allowed us to rerun our assessment removing low  
270 quality data traits from the analyses.

271

272 Species were considered sensitive, low in adaptability, or exposed to climate change if they scored  
273 ‘high’ for any trait under the respective framework dimension. To examine the effect of individual  
274 trait variables on the assessment, and to account for the possibility that species may show behavioural  
275 adaptation to reduce vulnerability to climate change, we dropped each trait variable in turn for each  
276 dimension and summarised the analysis again for comparison.

277

278 Species were considered as ‘climate change vulnerable’ if they scored ‘high’ across all three  
279 dimensions. Unknowns were treated in two ways: as low vulnerability for all traits, giving an  
280 ‘optimistic’ scenario (results in main manuscript), and as high vulnerability, giving a pessimistic  
281 scenario (results in the Supplementary Materials). Analyses presented in the main manuscript use  
282 climate change emission scenario A1B for 2050. Additional analyses are presented in the  
283 Supplementary Materials. We subsequently compared climate change vulnerability of species with  
284 their listing on the IUCN Red List.

### 285 *2.7 Data analysis*

286 To evaluate whether certain families are significantly more vulnerable to climate change than  
287 expected by chance, we tested for significant variation in vulnerability levels across families  
288 using a chi-square test, followed by further analyses to determine which families deviated from  
289 the expected level of vulnerability. Using binomial tests, we calculated the smallest family size  
290 necessary to detect a significant deviation from the observed proportion of climate-change  
291 vulnerable species and excluded families represented by an insufficient number of species from  
292 subsequent analysis. We generated a null frequency distribution of the number of vulnerable  
293 species from 10,000 unconstrained randomizations, by randomly assigning ‘high’ and ‘low’  
294 vulnerability to all species, based on their frequency of occurrence in the sample. We then  
295 counted the number of observed vulnerable species for each family and compared this with the

296 null frequency distribution. The null hypothesis (climate change vulnerability is taxonomically  
297 random) was rejected if this number fell in the 2.5% at either tail.

## 298 2.8 Spatial analysis

299 To examine the spatial distribution of climate change vulnerable species versus the distribution of  
300 threatened species on the IUCN Red List within our sample, we overlaid a hexagonal grid onto the  
301 stacked species' distributions of climate change vulnerable and IUCN Red List threatened species,  
302 and calculated respective species richness for each hexagonal grid cell (approximately 7,800 km<sup>2</sup> in  
303 size). The grid used was defined on an icosahedron, projected to the sphere using the inverse  
304 Icosahedral Snyder Equal Area (ISEA) projection to account for the Earth's spherical nature. To  
305 evaluate whether climate change vulnerable and IUCN Red List threatened species patterns overlap,  
306 we delineated 10% hotspots for each, defined as the 10% richest grid cells, and overlaid IUCN  
307 threatened species hotspots with climate change vulnerability hotspots.

308

309

## 310 3. Results

### 311 3.1 Data availability and quality

312 Trait data differed widely in their availability. Data gaps were largest for temperature-dependent sex  
313 determination (78.8% unknown), microhabitat specialisation (32.0% unknown), reproductive output  
314 (16.3% unknown) and longevity (13.2% unknown). For all other traits, percentages of unknown were  
315 less than 10% (Table S6). Data quality was considered overall low for microhabitat specialisation and  
316 interspecific dependencies (which could not be derived consistently from the IUCN Red List  
317 information given) and temperature-dependent sex determination (for which little data were available  
318 in the literature). In the following, we ran vulnerability analyses including and excluding these low  
319 data quality traits to examine their effects on the assessment.

### 320 3.2 Summary of sensitivity dimension

321 Nearly all species (80.5%) were scored as highly sensitive to climate change, primarily due to  
322 habitat specialisation (a trait possessed by 41.5% of species). Overall, 550 species were deemed  
323 highly sensitive to climate change because of a single trait triggering high sensitivity (Table S7).  
324 Narrow precipitation tolerance and habitat specialisation contributed to most species being  
325 deemed highly sensitive (162 and 158 of the 550 species, respectively). Dropping habitat  
326 specialisation and precipitation tolerance from the trait list each resulted in 87% of species being  
327 retained as highly sensitive, and 70% of species being highly sensitive overall. Removal of  
328 microhabitat specialisation, sensitivity to changes in fire regime, sensitivity to changes in  
329 flooding regime, temperature-dependent sex determination and interspecific dependencies had  
330 virtually no effect on the outcome of the sensitivity dimension, retaining 98-99% of highly  
331 sensitive species.

332 Excluding traits with low data quality (microhabitat specialisation, interspecific dependencies and  
333 temperature-dependent sex determination) led to 78.9% of species being listed as highly sensitive  
334 to climate change, and excluded only 24 species previously ranked as highly sensitive (of which  
335 17 are Least Concern on the IUCN Red List; Table S5). Only one of these species has a listed  
336 threat of climate change on the IUCN Red List (*Eretmochelys imbricata*, listed as Critically  
337 Endangered).

### 338 3.3 Summary of adaptability dimension

339 Forty-eight percent of species were found to have poor adaptability. Of these, 610 species were  
340 deemed to have low adaptability to climate change because of a single trait triggering the  
341 threshold: generation turnover contributed to most species being deemed of low adaptability (278  
342 of the 610 species), with reproductive capacity and barriers to dispersal contributing another 240

343 and 92 species, respectively. Excluding barriers to dispersal from the assessment had the least  
344 impact on the adaptability dimension, retaining 87% of low adaptable species and rendering  
345 41.5% of species overall as having low adaptability. The removal of generation length and  
346 reproductive output led to a retention of 61.1% and 66.4% of low adaptable species respectively  
347 (29-32% of species deemed to have low adaptability overall).

### 348 *3.4 Summary of exposure dimension*

349 Fifty-eight percent of species were listed as having high exposure to climate change. Of these,  
350 415 species triggered high exposure because of meeting the threshold values for a single exposure  
351 trait only, primarily due to the traits of temperature change and temperature variability (127 and  
352 134 species respectively; Table S7). Dropping exposure to sea level rise from the assessment had  
353 the least impact on the exposure dimension, retaining 98% of highly exposed species and  
354 rendering 56.7% of species overall as having high exposure. Removing changes in mean  
355 temperature and changes in temperature variability led to a retention of 83.0% and 82.3% of  
356 highly exposed species respectively (47-48% of species deemed having high exposure overall).

### 357 *3.5 Summary of climate change vulnerability in reptiles*

358 Overall, 246 of the 1498 species (16.4%) were deemed biologically susceptible to climate change  
359 (combining sensitivity with low adaptability), but were not exposed. Combining all three  
360 dimensions, 22.0% of species were listed as highly vulnerable to climate change (Figure 1A). A  
361 full data summary can be found in the Supplementary Materials (Table S6).

362 Excluding sensitivity traits with low data quality (microhabitat specialisation, interspecific  
363 dependencies and temperature-dependent sex determination) still led to 324 species overall listed  
364 as climate change vulnerable (Figure 1B). Another 242 species were biologically susceptible to  
365 climate change (i.e. had high sensitivity and low adaptability, but were not exposed; Figure 1B).

### 366 *3.3 Climate change vulnerable species*

367 Overall, percentages of climate change vulnerable species varied between 7.1% for amphisbaenians to  
368 19.6% for turtles and tortoises, 20.5% for lizards, 25% for snakes and 75% for crocodiles, the latter  
369 being based on a very small sample size of  $N = 4$  (Table 2). Percentage of climate change vulnerable  
370 species was lowest in the Oceanian (0%) and Afrotropical (11.4%) realms and highest in the  
371 Neotropical (31.5%), Palearctic (28.4%) and Nearctic (26.5%) realms. In the marine realm, 34.8% of  
372 species were highly vulnerable to climate change, compared to 28.8% in freshwater and 21.9% of  
373 terrestrial species.

374 At the family level, and excluding families represented by less than 10 species in our sample,  
375 Dactyloidae (53.8%), Sphaerodactylidae (44.7%), Viperidae (41.3%), Elapidae (33.3%),  
376 Colubridae (32.1%) and Gymnophthalmidae (30.8%) were the most vulnerable families within  
377 the analysis, with Atractaspididae, Calamariidae, Lamprophiidae, Leptotyphlopidae and  
378 Pseudoxyrhopiidae containing no vulnerable species. Excluding traits with low quality data  
379 retained all these families amongst the most and least vulnerable families. Including all traits, 38  
380 of the 70 families in the analysis were significantly more vulnerable than expected by chance ( $\chi^2$   
381 = 143.4,  $df = 69$ ,  $p$ -value < 0.001), with one family, the Pseudoxyrhopiidae, significantly less  
382 vulnerable than expected by chance (Table S8). Lamprophiidae were also less vulnerable than  
383 expected by chance, yet occurred at too small a sample size to reject our null hypothesis.  
384 Exclusion of traits with low data quality had no effect on the result. Overall vulnerability was  
385 highest in the parts of the Amazon basin and northwestern South America, south-western USA,  
386 and parts of Southern Asia (e.g., Sri Lanka, southern Western Ghats and Himalayan Arc; Figure  
387 2A).

### 388 *3.3 Comparison of climate change vulnerability assessment with IUCN threatened species status*

389 Of the 1,498 species in the assessment, 219 are currently listed as threatened on the IUCN Red  
390 List. Of these, only 60 species were found to be both vulnerable to climate change (58 species  
391 when excluding low data quality traits) and threatened on the IUCN Red List. Spatially, large  
392 areas of high climate change vulnerability, specifically in the Amazon basin, southwestern  
393 USA/northwestern Mexico, and Iran, do not have a corresponding high richness of IUCN Red  
394 List threatened species (Figure 2B).

#### 395 **4. Discussion**

396 We present the first trait-based global climate change vulnerability assessment for reptiles,  
397 supplementing earlier studies on climate change in lizards (Sinervo et al. 2010). Our analysis shows  
398 that reptiles are overall highly sensitive to climate change, but limited overlap of sensitivity with low  
399 adaptability and high exposure limits the number of overall climate change vulnerable species.  
400 Percentage of highly sensitive species was much larger than in previous global studies on birds (64%)  
401 and amphibians (72%) (Foden et al. 2013) and marginally higher than in regional studies on reptiles  
402 (West Africa: 77.5%; Carr et al. 2014; Tanzania: 71%; Meng et al. 2015, this issue).

403 Trait-based approaches allow us to tailor assessments to specific taxa, by including traits and variables  
404 relevant to the species group in question. However, this means assessments are not directly  
405 comparable between studies or taxa (Foden et al. 2013). Any comparisons with other studies, even in  
406 terms of levels of sensitivity to climate change etc. have to be taken with a degree of caution. While  
407 we endeavoured to replicate the approach by Carr et al. (2014) and Foden et al. (2013) as much as  
408 possible, our study differed in terms of data collection and how assessments were carried out. While  
409 Carr et al. (2014) and Foden et al. (2013) greatly relied on workshops and expert input to collate data,  
410 we relied heavily on existing data sources, including an extensive database on reptile traits developed  
411 for previous studies (Böhm et al. 2016), open-access spatial data and literature sources. While more  
412 cost-effective, our approach may be more precautionary than assessments derived through workshops,  
413 and may for certain traits result in low data quality (e.g. microhabitat specialisation, interspecific  
414 dependencies, and temperature-dependent sex determination). However, excluding traits of low data  
415 quality had negligible effects on the overall outcome of the assessment. Furthermore, traits associated  
416 with climate change vulnerability overlap with those associated with extinction risk, suggesting that  
417 trait-based approaches such as our current analysis and consideration of species-specific traits in  
418 IUCN Red List assessments may provide us with robust and informative assessments of species at risk  
419 from climate change (Pearson et al. 2014; Stanton et al. 2015).

420 Our assessment uses a representative sample of 1498 randomly selected species to assess climate  
421 change vulnerability. This approach was found to derive a broadly representative picture of extinction  
422 risk (Baillie et al. 2008) and its applicability to climate change vulnerability assessment is currently  
423 being investigated, specifically in the context of arbitrarily set percentage thresholds for sensitivity,  
424 adaptability and exposure traits. Because of the random nature of the sample, percentage thresholds  
425 should not affect the outcome of the assessment and should be broadly similar to other global  
426 assessments of species groups with similar distribution patterns. For example, our thresholds for  
427 tolerance of temperature changes and mean precipitation change were  $\leq 1.28^{\circ}\text{C}$  and  $\geq 0.55$  mm,  
428 respectively, similar to thresholds for these traits in other global assessments (e.g. birds:  $\leq 1.44^{\circ}\text{C}$ ,  $\geq$   
429 0.49 mm; amphibians:  $\leq 1.20^{\circ}\text{C}$ ,  $\geq 0.59$  mm; Foden et al. 2013).

##### 430 *4.1 Hypotheses, data gaps and quality*

431 Perhaps the biggest challenges for trait based assessments of climate change vulnerability are the lack  
432 of available life-history data (Still et al. 2015) and the fact that climate change may not affect every  
433 species in the same way, thus introducing uncertainty about underlying hypotheses about vulnerability  
434 traits. In the latter case, for example, temperature increases at high altitudes may not necessarily lead  
435 to altitudinal range shifts, as they may instead cause an increase in species survival rates through  
436 warmer temperatures. However, to perform effective large-scale regional or global trait-based

437 assessments of species vulnerability requires a framework combining best knowledge about the  
438 relationship between traits and vulnerability with a precautionary rather than evidentiary approach.

439

440 Considerable data gaps exist in our analysis, especially for traits which are not routinely collected for  
441 the purpose of Red List assessments. For example, 16.3% of species lacked data for reproductive  
442 output, and for 32% of species we were unable to define microhabitat dependence due to lack of  
443 detailed information (probably reflecting, in many cases, lack of information available, especially for  
444 highly data deficient species). Additionally, we excluded ‘dependence on environmental trigger’ as a  
445 trait in our analysis due to a near complete lack of data. While our approach relied on data available  
446 via published sources, workshops, although costly, may harness more data. For example, only 3% of  
447 species had unknown microhabitat dependencies in an assessment of West African reptiles which  
448 involved data collation during a workshop (Carr et al. 2014). Many data gaps can be filled by running  
449 climate change vulnerability assessments in conjunction with Red List assessments, which would  
450 encourage co-ordinated data collection (e.g. through integrated workshops). On the other hand, we  
451 used data that were literature-based or open access, which may provide a cost-effective way of  
452 assessing species. At the same time, experts could be engaged to ensure data are current and data gaps  
453 are filled.

454

455 Overall, four sensitivity traits each identified 5% of species or less as highly vulnerable. This could be  
456 due to a number of factors such as limited data availability for certain traits (reflecting data  
457 deficiency), collinearity of traits, or an indication that some of the traits may simply not relate to  
458 climate change vulnerability in reptiles. Such traits included interspecific dependencies, reliance on a  
459 specific fire or flooding regimes, and temperature-dependent sex determination. To obtain broad  
460 taxonomic patterns of climate change vulnerability and define spatial priorities at the global level, a  
461 trimmed down approach containing fewer traits that contribute extensively to the assessment (for  
462 example, habitat specialisation, slow turnover of generations, variables based on climatic data), and  
463 which relies on spatial data of climate change threat (e.g. Murray et al. 2014), may be a more time and  
464 cost-effective approach. This was also highlighted by the trimmed down approach excluding low data  
465 quality traits, which resulted in only a small number of species being removed from the list of climate  
466 change vulnerable species. However, climate change can affect species in very specific ways  
467 depending on biology and geography, and so the fullest possible complement of traits is required to  
468 draw species-level conclusions about conservation management. For example, 25.6% of reptile  
469 species in the Albertine Rift were intolerant of changes in a fire regime (Carr et al. 2013), thus highly  
470 sensitive to climate change, while in other assessments, including ours, this factor contributed little. In  
471 our analysis, inclusion of temperature-dependent sex determination rendered the turtle *Eretmochelys*  
472 *imbricata* highly vulnerable to climate change, while exclusion of this trait led to it having low  
473 sensitivity.

474

475 It has been argued that climate change velocity may outperform model scenarios in their ability to  
476 estimate exposure to climate change, because the velocity of climate change more closely predicts a  
477 species ability to adapt to change or migrate to suitable climate (Hamann et al. 2015). Future analysis  
478 on the robustness of climate change vulnerability assessments should compare different methods of  
479 estimating exposure, using data directly extracted from climate change scenarios as well as algorithms  
480 of climate change velocity. Climate change velocity can also be easily interpreted as one of a number  
481 of risk factors putting species at risk of decline and extinction (Hamann et al. 2015), thus potentially  
482 helping to improve extinction risk assessments (e.g. for the IUCN Red List) and analyses of the  
483 impact of climate change on population decline.

484

#### 485 4.2 Consequences for conservation action

486 Only 3.6% of reptiles in our sample were listed as threatened on the IUCN Red List due to climate  
487 change (Böhm et al. 2013), compared to 22% deemed climate change vulnerable in our current  
488 assessment. Thirty-eight of the 70 taxonomic families were significantly more vulnerable to climate  
489 change than expected by chance, showing that climate change vulnerability cuts across taxon groups.  
490 Discrepancy between low vulnerability in the climate change vulnerability assessment and climate

491 change threat on the IUCN Red List was mainly due to a lack of exposure to climate change in the  
492 climate change vulnerability assessment, and suggests that assessments of exposure should feature  
493 more prominently in IUCN Red List assessments. Furthermore, 62% of the 330 species found to be  
494 vulnerable to climate change were not listed in a ‘Threatened’ or Data Deficient Red List category.  
495 These should be given special scrutiny in future reassessments of their Red List status to ensure that  
496 their vulnerability is adequately represented within the assessment. In addition, climate change  
497 vulnerability assessments can highlight further – and often emerging – priorities for conservation  
498 action (Carr et al. 2014; Pacifici et al. 2015). For example, in addition to the 228 species listed as  
499 threatened by Böhm et al. (2013), we identify a total of 330 species that likely require attention due to  
500 their climate change vulnerability, with limited overlap between the two sets (Figure 2B). Additional  
501 monitoring is required depending on where they fall within the three dimensions of climate change  
502 vulnerability (Foden et al. 2013; Figure 1): potential adapters require monitoring of their adaptive  
503 response to climate change (395 species in this study), potential persisters should have their  
504 population trends monitored (65 species), while monitoring of the climatic environment is vital for  
505 biologically susceptible species (246 species) (Foden et al. 2013).

506 Increased protection of species through establishment of protected areas may be needed where  
507 numbers of potential adapters are high to give these species the best possible chance to adapt to  
508 changing climate over time. Given there was little spatial congruence between the main richness  
509 hotspots of climate change vulnerable and Red List threatened species, a number of new key areas  
510 may require management to minimise climate change effects, at least for reptiles (Figure 2B). Hotspots  
511 of highly vulnerable species were primarily confined to the Amazon basin and  
512 southeastern/southwestern USA, while hotspots of threatened species richness are spread across the  
513 world’s tropical regions (Böhm et al. 2013). Spatial conservation prioritisation should take into  
514 account both types of hotspots and appropriate conservation actions.

#### 515 *4.3 Conclusions and next steps*

516 Climate change vulnerability assessments are useful in supplementing IUCN Red List assessments by  
517 highlighting species which may become highly threatened over time. While labour-intensive, the  
518 approach is relatively easily carried out, provided adequate data are available for species-specific  
519 traits relating to climate change. To close data gaps, we need to engage in a three-pronged approach  
520 by 1) mobilising targeted data collection on traits by collaboration with field herpetologists, including  
521 traits excluded here, such a dispersal ability and dependence on environmental triggers, 2) making  
522 resulting species trait databases openly available, thus giving transparency to the process, enhancing  
523 scrutiny of the data and encouraging input from species experts, and 3) define best practice for  
524 collecting missing trait data to reduce uncertainty in assessments (Penone et al. 2014). Similarly, the  
525 most current data possible must be utilised to reassess exposure as improved projections become  
526 available.

527 The appropriateness of using a random sample for climate change vulnerability assessments needs to  
528 be assessed, akin to the Sampled Red List Index approach (Baillie et al. 2008), to derive broad-scale  
529 patterns of climate change vulnerability, and to investigate the relative importance of individual traits  
530 to overall vulnerability. For example, incorporating weighting of traits into an assessment could be  
531 highly useful, as some traits are likely to respond more intensely to climate change than others  
532 (Tuberville et al. 2015). This will also help determine whether less data-intensive and more time-  
533 efficient methods may yield broadly similar results for the purpose of global policy planning, rather  
534 than making species-specific conservation decisions (for which a full complement of trait data would  
535 be needed). This should include consideration of ecosystem or community-level assessments of  
536 climate change vulnerability. Current species-specific work is focused on comparing outcomes from  
537 different trait-based approaches, and how methods could be further standardised to allow more  
538 consistent assessments of climate change vulnerability within and between species.

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683 **Table 1.** Species traits for which data were collected, by dimension (sensitivity, poor adaptability, exposure) and trait group (A. Specialised  
684 habitat/microhabitat requirements; B. Narrow environmental tolerances or thresholds; C. Dependence on interspecific interactions; D. Poor dispersal ability;  
685 E. Poor evolvability), including hypotheses for inclusion in the assessment and thresholds applied. Traits were scored as contributing to high or low  
686 vulnerability as shown in the threshold column.

<i>Trait set</i>	<i>Variable</i>	<i>Description</i>	<i>Vulnerability threshold</i>	<i>Hypotheses</i>
A	S1. Habitat specialisation	Number of habitats a species occurs in	Low > 1 habitat type High = 1 habitat type	Habitat generalists are more likely to adapt to changing habitat conditions with climate change as they have more habitat options available to them
A	S2. Microhabitat specialisation	Species is dependent on one or more of the identified microhabitats <sup>1</sup>	Low = false High = true	Species which occur in microhabitats affected by climate change will be more affected by climate change overall
A	S3. Restriction to high-altitude habitat	Species is found only at 1,000 metres above sea level or above	Low = false High = true	Species which occur solely in high-altitude habitat will be more affected by climate change due to consequences of altitudinal range shifts
B	S4. Tolerance of changes to precipitation regimes	Average absolute deviation in precipitation across the species' historical range	Low = highest 75% (>30.97 mm) High = lowest 25% (<30.97 mm)	Species with narrow tolerance to precipitation regimes will be most affected by precipitation changes due to climate change
B	S5. Tolerance of temperature changes	Average absolute deviation in temperature across the species' historical range	Low = highest 75% (>1.28 °C) High = lowest 25% (<1.28 °C)	Species with narrow tolerance to temperature regimes will be most affected by precipitation changes due to climate change
B	S6. Sensitivity to change in fire regime	Species relies upon a specific fire regime (or lack of) across its entire range	Low = false High = true	Fire regimes are likely to change with changing climate, thus directly affecting species dependent on specific regimes
B	S7. Sensitivity to change in flooding regime	Species relies upon a specific flooding regime (or lack of) across its entire range	Low = false High = true	Flooding regimes are likely to change with changing climate, thus directly affecting species dependent on specific regimes
B	S8. Temperature-dependent sex determination	Sex of offspring is known to be dependent upon temperature during incubation	Low = false High = true	Species with temperature-dependent sex determination will be more vulnerable to the effects of climate change due to temperature changes affecting population sex ratios
C	S9. Dependence on narrow	Species diet consists of a low number of species from a single dietary category	Low = false	Species with dietary specialisation are likely to be more affected by changes in prey base due to climate change

	range of food types		High = true	
C	S10. Interspecific dependencies	Species is dependent upon another to modify or create habitat suitable for itself OR could experience increases in one or more of the following as a result of climate change: Predation, competition, parasitism, disease	Low = false High = true	Species whose population dynamics are dependent on interspecific interactions are likely to be more affected by changes in abundance and distribution of the other species in question
<i>Adaptability</i>	<i>Variable</i>	<i>Description</i>	<i>Threshold</i>	<i>Hypotheses</i>
D	A1. Barriers to dispersal	Species occurs in isolated areas due to the presence of barriers to dispersal (i.e. a species is isolated because it occurs exclusively on mountaintops, small islands and/or polar edges of land masses)	Low = false (no known barriers) High = true	Species which are not isolated due to presence of extrinsic barriers to dispersal are more likely to be able to disperse out of areas experiencing climate change
E	A2. Slow turnover of generations	Generation length (here replaced by longevity as a proxy for generation length)	Low = shortest 75% (<10 years) High = longest 25% (>10 years)	Species with longer generation length/longevity are likely to have slower life histories and lower reproductive frequency/output, hence affecting their ability to produce offspring fast enough to potentially trigger adaptation by genetic variability
E	A3. Reproductive capacity	Reproductive output (mean clutch/litter size x mean no. clutches/litters per year)	Low = highest 75% (>3.8) High = lowest 25% (<3.8)	Species with low reproductive output will be more affected by climate change since they will not produce enough offspring to potentially trigger adaptation by genetic variability
<i>Exposure</i>	<i>Variable</i>	<i>Description</i>	<i>Threshold</i>	<i>Hypotheses</i>
	E1. Exposure to sea level rise	Habitat types are exposed to sea level inundation (i.e. species occurs only in inundation exposed coastal habitats and in no or only one other habitat type)	Low = false High = true	Habitats which are coastal and already exposed to inundation by the sea will become even more affected due to sea level rise; specialists of these habitat types will thus be more affected by climate change
	E2. Changes in mean temperature	Substantial changes in mean temperature occur across the species' range (measured as absolute difference in mean temperatures across the species' range for all months between 1975-2050)	Low = lowest 75% (<27.25°C) High = highest 25% (>27.25°C)	In areas where temperature changes are largest, climatic change exposure is going to be highest and species are more likely to be affected

E3. Temperature variability change	Substantial changes in temperature variability across the species' range (measured as absolute difference in average absolute deviation in temperature across the species' range for all months between 1975 to 2050)	Low = lowest 75% (<7.32°C) High = highest 25% (>7.32°C)	In areas where temperature changes are largest, climatic change exposure is going to be highest and species are more likely to be affected
E4. Changes in mean precipitation	Substantial changes in mean precipitation occur across the species' range (measured as absolute ratio of change in mean precipitation across the species' range for all months between 1975-2050)	Low = lowest 75% (<0.55 mm) High = highest 25% (>0.55 mm)	In areas where precipitation changes are largest, climatic change exposure is going to be highest and species are more likely to be affected
E5. Precipitation variability change	Substantial changes in precipitation variability across the species' range (measured as absolute ratio of change in average absolute deviation in precipitation across the species' range for all months between 1975 to 2050)	Low = lowest 75% (<0.47 mm) High = highest 25% (>0.47 mm)	In areas where precipitation changes are largest, climatic change exposure is going to be highest and species are more likely to be affected

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687 <sup>1</sup> mountain rapids/rivulets, ephemeral pools, bamboo, vines, fallen trees, dead wood, tree hollows, trees bordering water, riverine or gallery forests, ant  
688 hills/termitaria, dunes, open patches in grassland, rocky areas and outcrops, cliffs, and caves; freshwater- or forest-dependent.

**Table 2.** Climate change vulnerability in a subsample of 1498 reptile species by order, biogeographic realm and habitat system. Results for the full assessment including all traits are shown, and supplemented with results of the assessment excluding low data quality traits where these were different (bottom row italics).

<b>Taxon</b>	<b>High</b>	<b>Low</b>	<b>N</b>	<b>% vulnerable</b>
Reptiles	330 <i>(324)</i>	1,168 <i>1,174</i>	1,498	22.1% <i>21.6%</i>
Amphisbaenia	2	26	28	7.1%
Crocodylia	3 <i>(1)</i>	1 <i>3</i>	4	75% <i>25%</i>
Sauria	177 <i>(175)</i>	688 <i>690</i>	865	20.5% <i>20.2%</i>
Serpentes	139 <i>(137)</i>	416 <i>418</i>	555	25.0% <i>24.7%</i>
Testudines	9	37	46	19.6%
<b>Realm</b>				
Afrotropical	33 <i>(32)</i>	257 <i>258</i>	290	11.4% <i>11.0%</i>
Australasian	33 <i>(32)</i>	188 <i>167</i>	220	15.0% <i>14.5%</i>
Indomalayan	52 <i>(50)</i>	262 <i>264</i>	314	16.6% <i>15.9%</i>
Nearctic	26	72	98	26.5%
Neotropical	166 <i>(165)</i>	361 <i>362</i>	527	31.5% <i>31.3%</i>
Oceanian	0	8	8	0.00%
Palearctic	44 <i>(42)</i>	111 <i>113</i>	155	28.4% <i>27.1%</i>
<b>Habitat system</b>				
Terrestrial	322 <i>(316)</i>	1,149 <i>1,155</i>	1,471	21.9% <i>21.5%</i>
Freshwater	23 <i>(21)</i>	57 <i>59</i>	80	28.8% <i>26.3%</i>
Marine	8 <i>(7)</i>	15 <i>16</i>	23	34.8% <i>30.4%</i>

## Figure legends

**Figure 1.** Climate change vulnerability of species according to the IUCN method (Foden et al. 2013). A: Using the full set of trait variables, species scored as ‘high’ across all three dimensions (sensitivity, poor adaptability and exposure) were classed as overall highly vulnerable to climate change (N=330; 22.0%). B: Excluding low data quality traits (microhabitat specialisation (S2), temperature-dependent sex determination (S8) and interspecific dependencies (S10)), 324 species were classed as highly vulnerable to climate change (21.6%). Seventy-four (full assessment, A) and 82 species (low data quality traits excluded, B) were scored as ‘low’ in all three dimensions. Species will have different monitoring requirements: potential adapters require monitoring of adaptive response to climate change, potential persisters require population monitoring; biologically susceptible species require environmental/climatic monitoring.

**Figure 2.** A. Richness pattern of species that are considered climate change vulnerable (highly sensitive, poorly adaptable and highly exposed). B. overlap (red) of 10% hotspots of climate change vulnerable (CCV) and threatened species on the IUCN Red List; climate change vulnerable species only (light grey), threatened species only (IUCN Red List categories Vulnerable, Endangered and Critically Endangered; dark grey).

**Figure 1.**

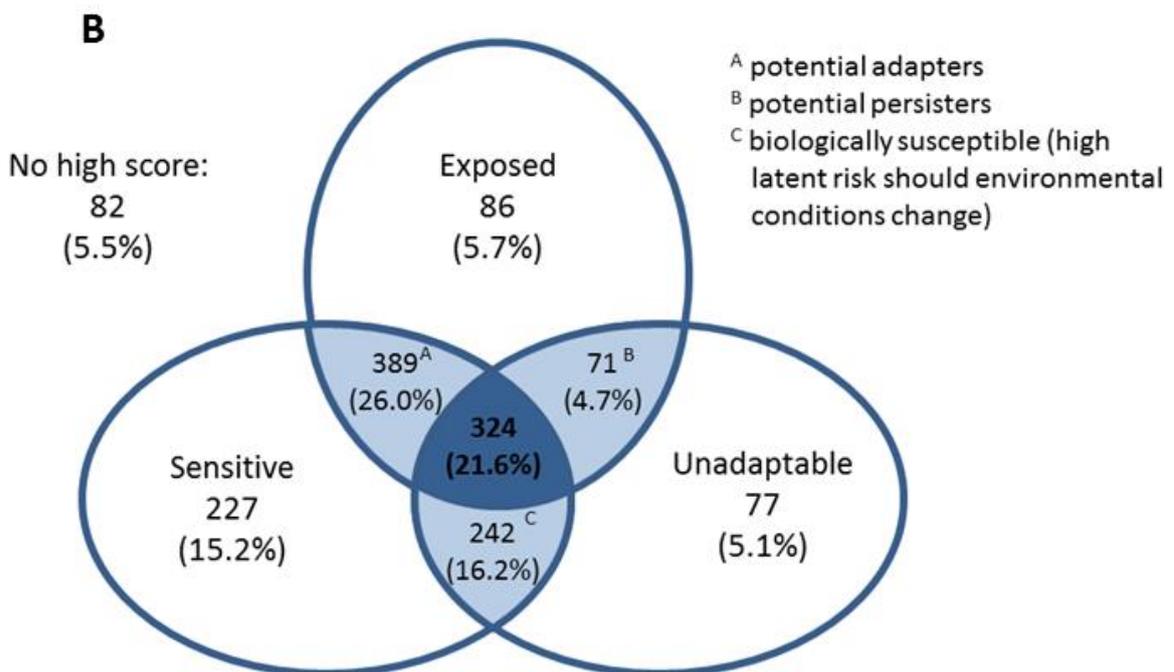
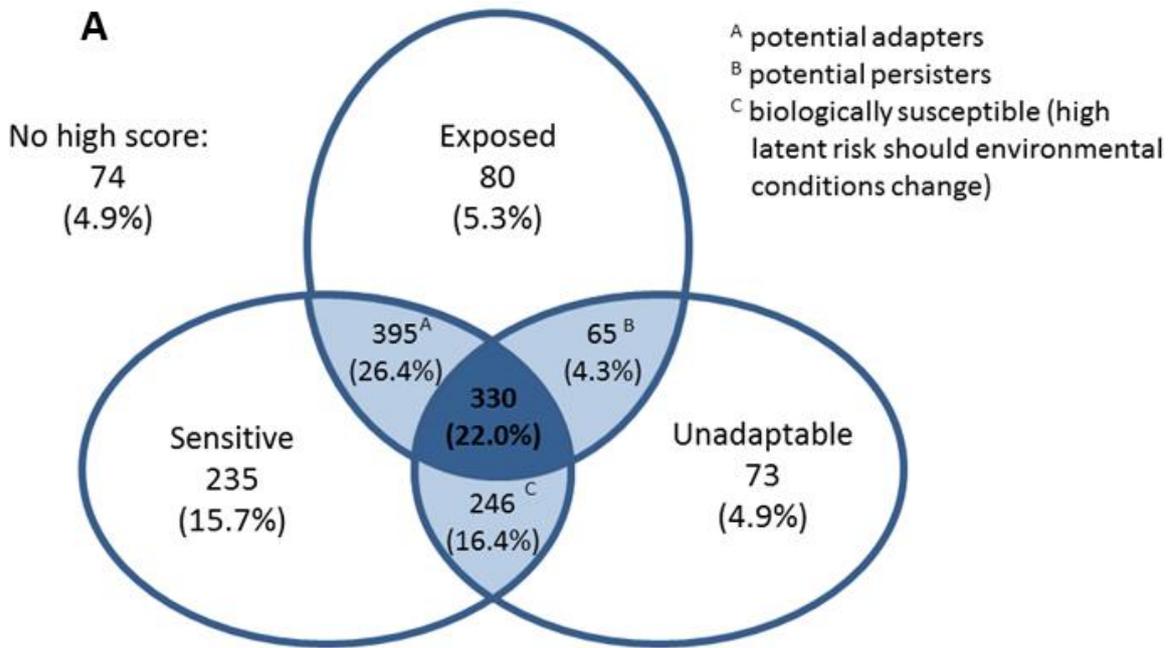


Figure 2.

