



University of Southern Denmark

## The myriad of complex demographic responses of terrestrial mammals to climate change and gaps of knowledge

### A global analysis

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### 63 **Keywords**

64 Climate vulnerability; temperature extremes; comparative demography; demographic rates;  
65 population growth rate

### 66 **Abstract**

- 67 1. Approximately 25% of mammals are currently threatened with extinction, a risk that is  
68 amplified under climate change. Species persistence under climate change is determined  
69 by the combined effects of climatic factors on multiple demographic rates (survival,  
70 development, reproduction), and hence, population dynamics. Thus, to quantify which  
71 species and regions on Earth are most vulnerable to climate-driven extinction, a global  
72 understanding of how different demographic rates respond to climate is urgently needed.
- 73 2. Here, we perform a systematic review of literature on demographic responses to climate,  
74 focusing on terrestrial mammals, for which extensive demographic data are available.
- 75 3. To assess the full spectrum of responses, we synthesize information from studies that  
76 quantitatively link climate to multiple demographic rates. We find only 106 such studies,  
77 corresponding to 87 mammal species. These 87 species constitute < 1% of all terrestrial  
78 mammals.
- 79 4. Our synthesis reveals a strong mismatch between the locations of demographic studies  
80 and the regions and taxa currently recognized as most vulnerable to climate change.  
81 Surprisingly, for most mammals and regions sensitive to climate change, holistic  
82 demographic responses to climate remain unknown. At the same time, we reveal that  
83 filling this knowledge gap is critical as the effects of climate change will operate via  
84 complex demographic mechanisms: a vast majority of mammal populations display  
85 projected increases in some demographic rates but declines in others, often depending  
86 on the specific environmental context, complicating simple projections of population fates.
- 87 5. Assessments of population viability under climate change are in critical need to gather  
88 data that account for multiple demographic responses, and coordinated actions to assess  
89 demography holistically should be prioritized for mammals and other taxa.

90

## 91 **Introduction**

92 The ca. 6,400 extant mammal species have colonized virtually all terrestrial and most aquatic  
93 habitats (Jenkins *et al.* 2013). This evolutionary success has been facilitated by the wide range of  
94 mammalian life history strategies (Healy *et al.* 2019), which enable them to cope with vastly  
95 different climates (Promislow *et al.* 1990). These strategies include extreme examples like male  
96 semelparity in some Australian marsupials, characterized by short, explosive mating seasons  
97 (Fisher *et al.* 2013), or high behavioral and demographic plasticity in long-lived primates that buffers  
98 populations from the negative effects of environmental variation (Campos *et al.* 2017). This  
99 tremendous variation in life history strategies can be captured by differences among organisms in  
100 their rates and timing of survival, development, and reproduction (Stearns 1992). It is these  
101 demographic rates that determine population growth and thus species persistence (Morris & Doak  
102 2002). Therefore, understanding the effects of climate drivers on the viability of natural mammal  
103 populations requires a simultaneous consideration of multiple demographic rates (Paniw *et al.*  
104 2019).

105 Important efforts have been made in the last decade to increase the amount of comparative data  
106 to understand the variation in demographic rates across mammals (Conde *et al.* 2019). These data  
107 have resulted in the broader availability of open-access demographic information on populations of  
108 mammals and other taxa (Jones *et al.* 2009; Salguero-Gómez *et al.* 2016) and have produced key  
109 life-history knowledge, for instance on lifespan and mortality schedules (Conde *et al.* 2019; Jones  
110 *et al.* 2014). However, we still lack a holistic understanding of how climate drivers simultaneously  
111 affect survival, development, and reproduction in mammals worldwide. This gap is at odds with an  
112 emerging consensus that interactions among demographic rates and biotic and abiotic drivers  
113 hinder simplistic projections of persistence under climate change (Benton *et al.* 2006; Urban *et al.*  
114 2016). For instance, a negative effect of climate on a specific demographic rate does not  
115 necessarily cause a population to go extinct, when another demographic rate responds positively  
116 to climate, or when population dynamics are mediated by interactions among climate drivers and  
117 density-dependent feedbacks (Reed *et al.* 2013; Paniw *et al.* 2019). Consequently, it is important  
118 to assess whether the complexity of demographic responses to climate is widespread among  
119 mammals and whether research quantifying such complexity is available for regions most  
120 vulnerable to climate change or for the most vulnerable species.

121 Here, we synthesize our understanding regarding where, which, and how mammal populations  
122 respond to climate. We searched for literature linking multiple demographic rates to climatic drivers,  
123 thus capturing the complexity of demographic responses, for 5,728 terrestrial mammal species  
124 (Myhrvold *et al.* 2015). We then performed a rigorous review of studies that matched our search

125 criteria and linked data from the review to information on ecoregion and species' vulnerability to  
126 climate change (Beaumont *et al.* 2011; IUCN 2019). Our review allows us to explore (i) whether  
127 mammal demographic studies are conducted in ecoregions that are most vulnerable to projected  
128 increases in temperature and precipitation extremes (Q1: *Where?*); (ii) whether potential future  
129 demographic responses to climate change reflect species' extinction risk as determined by the  
130 IUCN Red List status of mammals (Q2: *Which species?*); and (iii) through which demographic  
131 processes projected changes in climate may show negative and/or positive effects on populations  
132 (Q3: *How?*).

### 133 **Methods**

134 We obtained scientific names of 5,728 terrestrial mammal species from the Amniote database  
135 (Myhrvold *et al.* 2015). For each species, we searched SCOPUS for studies (published before  
136 January 2018) that quantified demographic-rate-climate relationships (for the full list of search  
137 terms, see Supporting information S1). We also confirmed, using a subset of species, that a search  
138 in Web of Science did not produce different results (Supporting information S1). From any study  
139 that matched our search terms, we extracted information on demographic-rate-climate  
140 relationships only if (i) the study linked at least two different demographic rates (*i.e.*, survival,  
141 development/growth, or reproduction) to a climatic driver (*i.e.*, any direct or indirect measure of  
142 temperature or precipitation); and (ii) the response of a demographic rate to a climatic driver was  
143 quantified using statistical methods (*i.e.*, excluding qualitative or descriptive studies). To  
144 standardize our search protocol and to assess potential global demographic consequences of  
145 climate change, we recorded local climatic factors such as winds or storms only when these factors  
146 were related to temperature and precipitation. In addition, we only considered studies on natural  
147 populations of terrestrial mammals, or partially terrestrial mammals (e.g., polar bears), because  
148 initial results showed that there were few climate-related population studies on fully aquatic  
149 mammals, which considered distinct climatic drivers that lack future projection information (e.g.,  
150 ocean circulation indices).

151 From all studies meeting our criteria, we extracted the effects any climatic driver had on  
152 unstructured or age- or stage-specific demographic rates. We grouped these effects as positive  
153 (*i.e.*, increased rate), negative (*i.e.*, reduced rate), no effect, or context-dependent (e.g., increased  
154 rate at low population densities and no effect at high densities; see Supporting information S1 for  
155 details). We also recorded whether climate effects were measured at annual or seasonal scales  
156 and, when applicable, the factors that mediate these effects (e.g., density, biotic interactions). In  
157 studies that indicated future projections of drivers, we recorded whether drivers were projected to  
158 increase, decrease, or show context-dependent trends.

159 For the 68% of studies that did not report on climate projections (Figs. S1.4 & S1.5) but assessed  
160 demographic effects of direct temperature and precipitation measures, we approximated whether  
161 future averages and extremes in these drivers were likely to increase, decrease, or remain  
162 unchanged under global climate change (Supporting information S1). To do so, we obtained  
163 monthly average temperatures and precipitation data as well as maximum and minimum monthly  
164 temperatures from 1979-2013 for all relevant study locations using *climatologies at high resolution  
165 for the earth's land surface areas* (CHELSA; ca. 1 km<sup>2</sup> resolution) (Karger *et al.* 2017). The monthly  
166 scale corresponded to the finest scale used to aggregate climatic variables for demographic  
167 analyses in the reviewed studies. We also obtained projections of these variables for 2041-2060  
168 assuming five diverging climate models (NorESM1-M; MPI-ESM-LR; GISS-E2-R; CMCC-CM;  
169 CESM1-BGC; Supporting information S1). We averaged historical and projected climate records  
170 for each month and each of the five climate models. We then calculated changes in each of the  
171 climate variables by subtracting the monthly average historical records from the projected values.  
172 We set the change to 0 if 95 % CI of the monthly averages across the five projection models crossed  
173 corresponding average historical values. Finally, we averaged these changes across all months to  
174 obtain a unique value of projected increase, decrease, or no change in total precipitation or average  
175 and extremes in temperature. We also calculated the standard deviation of the monthly averaged  
176 historical and projected climate records and assessed the changes in this deviation using the 95 %  
177 CI as above, which gave us a unique value of increase, decrease, or no change in the variation of  
178 the above variables.

179 To quantify potential demographic effects of global changes in temperature and precipitation, we  
180 linked the changes in precipitation and temperature variables obtained from CHELSA to the  
181 reviewed studies in the following way: If a study assessed seasonal/annual averages or deviations  
182 in precipitation, mean temperature, or minimum/maximum temperature but did not project future  
183 changes in these variables, we assigned future changes using our CHELSA climate data –  
184 assuming that precipitation and temperature variables used in a given study would change in the  
185 same direction as the CHELSA climatic data. From this information, we then determined whether  
186 a demographic rate would potentially decrease (e.g., where a rate has a positive response to  
187 maximum temperature and maximum temperature projected to decrease) or increase (e.g., where  
188 a rate has a positive response to maximum temperature and maximum temperature projected to  
189 increase). Unless explicitly stated otherwise in a study, we assumed that demographic rates that  
190 were not affected by a climatic variable would not change in the future, and ones that showed  
191 context-dependent responses would also likely show context-dependent responses in the future.

192 A full list of extracted studies and a more detailed description of the extraction protocol and climate  
193 modelling can be found in Supporting information S1 and Table S1.1. We note that the multitude  
194 of methodological approaches used to study demographic responses (e.g. correlation analyses,

195 structured demographic models, individual-based models) and the lack of a full statistical report in  
196 some studies (Gerstner *et al.* 2017) render a full meta-analytical approach of climate-demography  
197 relationships impractical.

198 We determined how well our studies provided knowledge in global ecoregions with high biodiversity  
199 and high vulnerability to climate change (Q1, *Where?*) using two approaches. First, we built on the  
200 results of Beaumont and colleagues (2011), which found that temperature, unlike precipitation, is  
201 projected to become more extreme in all of the 132 terrestrial ecoregions of exceptional biodiversity  
202 (i.e., in the “Global 200”, Pimm *et al.* 2014). Specifically, the authors classified temperature  
203 vulnerability of the G200 ecoregions using, among other measures, the weighted average minimum  
204 monthly distance in temperatures (under the A2 climate model ensemble) from the mean of the  
205 1961-1990 baseline. The higher the distance, the more vulnerable an ecoregion (Beaumont *et al.*  
206 2011). We quantified the proportion of our studies that were conducted in these highly biodiverse  
207 ecoregions, and the proportion of these studies that assess the demographic effects of temperature  
208 increases. Further, we quantified and visualized whether demographic rates were reported to be  
209 decreasing (-), not changing (0), or increasing (+) under increasing temperatures across ecoregion  
210 temperature vulnerability scores.

211 Second, to assess how well our studies provided knowledge in areas projected to experience the  
212 highest changes in temperature and precipitation, regardless of whether they have high  
213 biodiversity, we obtained gridded global data on annual average surface air temperature and total  
214 precipitation anomalies, the latter driven by seasonal variation (Collins *et al.* 2013), for the period  
215 (2030-2049) compared to present day (1986-2005). Climatic anomalies were based on the  
216 Representative greenhouse-gas Concentration Pathway scenario 6.0 (NCAR 2012), which is  
217 similar to the previous SRES A2 climate model ensemble (Moss *et al.* 2008). We matched the  
218 geographic locations of the studied mammal populations to the gridded global anomalies.

219 To assess whether demographic responses to projected changes in climate agree with the  
220 International Union for Conservation of Nature and Natural Resources (IUCN) Red List status of  
221 mammals (Q2: *Which species?*), we obtained IUCN assessments (including threats) for all species  
222 identified in the literature review. We used the R package *rredlist* (Chamberlain 2020) to access  
223 the IUCN Red List database and extract available information on whether the species are listed in  
224 the database, and, if so, what status they are assigned to and whether climate change is listed as  
225 an existing or potential threat. Lastly, for each IUCN threat category, we quantified the diversity of  
226 projected positive (+), negative (-), and context-dependent (CD) climatic effects across different  
227 demographic rates and life-cycle stages modelled for the mammal populations (Q3: *How?*).



228

## 229 **Results**

230 For most terrestrial mammals, we did not find studies on detailed demographic responses to  
231 climate. We extracted information on climate-demography relationships from 106 studies, for a total  
232 of 87 mammal species, that quantified simultaneous responses to climate in at least two different  
233 demographic rates. These studies span 12 biomes, with the exception of tropical and subtropical  
234 coniferous forests and mangroves (Fig. S1.1). Overall, more studies assess only the direct effects  
235 of precipitation ( $n = 42$ ) than the direct effects of temperature ( $n = 11$ ) (Fig. S1.2); and in eight of  
236 the 106 studies, only indirect effects are assessed via indices such as the North Atlantic Oscillation  
237 (NAO) or El Niño–Southern Oscillation (ENSO), while only seven studies assess the combined  
238 demographic effects of temperature, precipitation and climate indices (Fig. S1.2). A majority of  
239 studies (71%) only test demographic responses to seasonal ( $n = 40$ ) or annual ( $n = 36$ ) averages  
240 or sums in climate variables, while 16 % of studies assess responses to climate extremes (maxima,  
241 minima, or deviation from averages) as well as averages (Fig. S1.3). Few studies (10%) test how  
242 different climatic drivers interact with one another, approximately half (55%) test for the effects of  
243 density dependence on demographic rates, and an additional 27% test for effects of non-climatic  
244 drivers other than population density (e.g. predation, food availability). Studies that test for driver  
245 interactions typically find context-dependent climate effects in some demographic rates, with 15%  
246 of all reviewed studies reporting such effects.

247

248 In addressing “Q1: *Where?*”, our synthesis reveals that few demographic studies are conducted in  
249 ecoregions that are both biodiverse and highly vulnerable to climate change (Olson and Dinerstein  
250 2002). We find that 42 out of the 106 demographic studies were conducted in one of the G200  
251 ecoregions (Fig. 1). However, only 13 of these studies assess the demographic effects of  
252 temperature increases. In addition, no study has examined the responses of different demographic  
253 rates in ecoregions with the highest vulnerability scores (e.g., the Central Congo Basin; darkest red  
254 in Fig. 1). Only one study, which included three primate species, assessed temperature effects in  
255 a G200 ecoregion with relatively high vulnerability to climate change; and found no effects (Fig. 1  
256 insert) likely due to the primates’ behavioural and physiological flexibility before climate variation  
257 (Campos *et al.* 2017). Similarly, our synthesis reveals that few demographic studies are conducted  
258 in ecoregions projected to have the greatest anomalies in annual temperature and precipitation  
259 (Fig. S1.6). Only one study (Hunter *et al.* 2010) assessed climate-demography relationships, of  
260 polar bears (*Ursus maritimus*), in an arctic region with highest projected increases in average  
261 temperature ( $> 2.5$  °C; Fig. S1.6a). Lastly, no study has examined demographic responses to  
262 precipitation in ecoregions with highest projected decreases in precipitation. Only two studies  
263 (Campos *et al.* 2017; Marshall *et al.* 2016), considering a banded mongoose and two primate

264 populations, examined demographic responses to precipitation in regions in East Africa, where  
265 precipitation is projected to increase substantially (> 100 mm; Fig. S1.6).

266

267 In addition to an ecoregion bias, in answering “Q2: *Which species?*”, we highlight that demographic  
268 analyses suffer from a taxonomic bias too. Studies linking multiple demographic rates to climatic  
269 drivers are primarily performed in regions with a relatively low mammal richness and on species  
270 that are not currently vulnerable to climate change (Fig. 2), based on IUCN classifications. Indeed,  
271 the IUCN has identified at least 17% of listed vertebrates to be sensitive to climate change, *i.e.*,  
272 decreasing in numbers or losing habitat under changes in temperature and precipitation regimes  
273 due to elevated atmospheric CO<sub>2</sub> levels (Marris 2008). Our synthesis reveals that only 4% of all  
274 mammals assessed as climate sensitive by the IUCN have detailed studies linking demography to  
275 climate (*i.e.*, 13% of studies we assessed). Interestingly, the proportion of demographic rates per  
276 study that may decline under global climate change (0.31, ± 0.10 S.E.) is highest for species that  
277 have been flagged by the IUCN as climate sensitive. However, this proportion is followed closely  
278 by species for which climate change is not considered a threat by the IUCN (Fig. 2 insert).

279

280 In addressing “Q3: *How?*”, our synthesis reveals that complex demographic responses to climate  
281 are prevalent. Only eight (7%) of the 106 studies report unidirectional (all positive) responses of  
282 demographic rates to climatic drivers, while in 19 cases no effect of climate on any demographic  
283 rate is reported (Figs. S1.4 & S1.5). For the vast majority of species, effects of climate reported in  
284 the studies (79%) and projected under global change as presented in the studies or approximated  
285 in our analysis (75%) can be positive, negative or context-dependent depending on the population  
286 studied and the specific driver, demographic rate, and life-cycle stage considered (examples in Fig.  
287 4). In addition, 13 studies assess the effects of climate on population growth rates in addition to  
288 underlying demographic rates (Fig. S1.4, Table S1.1). These examples show that population  
289 responses are not readily predictable from a single demographic rate when multiple climatic drivers  
290 and their interactions with biotic drivers affect demography. For instance, Lawler and co-authors  
291 (2009) show that survival, stage transitions, and reproduction all determine how the population  
292 growth rate of the long-lived Verreaux’s sifakas (*Propithecus verreauxi verreauxi*) responds to  
293 annual rainfall.

294

## 295 **Discussion**

296 Our synthesis shows that gaining a global understanding of the mammals that are most vulnerable  
297 to climate-driven extinction will require filling important knowledge gaps. Studies on climate effects  
298 across the whole life cycle of populations are needed in regions that are highly susceptible to  
299 climate change, many of which are biodiversity hotspots (Beaumont *et al.* 2011). Many of these  
300 ecoregions are not only threatened by increases in climate extremes (Beaumont *et al.* 2011; Stott

301 2016) but also face strong pressures on biodiversity from direct human activities (Venter *et al.*  
302 2016). A majority of studies linking demographic rates to climate in vulnerable ecoregions and  
303 elsewhere nevertheless focus on demographic responses to changes in average climate and do  
304 not account for interactions with non-climate drivers. It is possible that publication bias plays a part  
305 in our observations of these omissions, as authors may, for instance, explore interactions but not  
306 mention this in their published study due insignificant or inconclusive results (Jennions and Møller  
307 2002). At the same time, population dynamics are typically driven by compound effects of  
308 interacting climatic and non-climatic drivers (Benton *et al.* 2006; Zarnetske *et al.* 2012), which are  
309 projected to become more extreme under climate change (Zscheischler *et al.* 2018). A stronger  
310 focus on extremes and driver interactions is therefore required to improve our estimates of  
311 population viability.

312  
313 Our analysis also reveals that studies assessing responses to climate across different demographic  
314 rates are required for most mammals considered climate-sensitive by the IUCN. These results  
315 support recent calls to gain a better understanding of the complex effects of climate on population  
316 viability (e.g., Doak and Morris 2010; Cahill *et al.* 2013; Román-Palacios and Wiens 2020), allowing  
317 this threat to be understood and potentially mitigated through conservation. On the other hand,  
318 given that a large number of mammals not considered to be climate sensitive may actually show  
319 negative demographic responses to climate change, our results support the need for current IUCN  
320 efforts to re-evaluate the importance of climate as an extinction threat to mammals (Foden and  
321 Young 2016). It is noteworthy that the majority of demographic studies on mammals do not project  
322 demographic effects of climate change. Our simplified and broad approximation of climate change  
323 for these studies allowed for global synthesis in this review, but we note that this approximation  
324 does not match the spatiotemporal resolution of the climatic drivers assessed in the relevant  
325 studies, averages over seasonal climatic patterns, and does not allow examination of interactions  
326 with other important factors, which can exacerbate or dampen large-scale climate trends (van de  
327 Pol *et al.* 2013). Thus, an important challenge for future studies is to project changes in local climatic  
328 variables that have been considered important drivers of demographic rates (Snover *et al.* 2013).

329  
330 By focusing on studies that have assessed several demographic responses to climate, we  
331 necessarily limited the number of taxa in our review. In fact, we identified at least 111 more studies  
332 on 68 additional species that only assessed climatic effects on single demographic rates. We stress  
333 here that we do not question the validity of such studies when population dynamics can be  
334 accurately predicted from the changes in one demographic rate with a uniquely high contribution  
335 to the population growth rate. However, population responses to climate are typically determined  
336 by the covariation among multiple demographic rates, which itself is often mediated by a myriad of  
337 interacting biotic and abiotic factors (e.g., Reed *et al.* 2013). For instance, impalas (*Aepyceros*

338 *melampus*), which the IUCN characterizes as threatened by drought (Table S1.1), may show  
339 positive or negative responses in survival and reproductive success under rainfall scarcity  
340 depending on the seasonal patterning of rainfall and population density (Ogutu *et al.* 2012).  
341 Similarly, meerkats (*Suricata suricatta*), which currently face no threats according to the IUCN,  
342 show both positive and negative responses to precipitation across several critical demographic  
343 rates depending on social stage, group size, and temperature extremes (Ozgul *et al.* 2014; Paniw  
344 *et al.* 2019). Therefore, as a cooperative breeder, meerkats may be vulnerable to compound effects  
345 of increases in seasonal climatic extremes that decrease group densities (Paniw *et al.* 2019). Such  
346 complex demographic responses make it challenging to project species' fates under climate  
347 change because the future of populations cannot be accurately determined from single  
348 demographic rates (Urban *et al.* 2016).

349  
350 As consistently negative demographic responses to climate change are only relatively common in  
351 species the IUCN flagged as climate sensitive, our results suggest that complexity of demographic  
352 responses may buffer populations from adverse climate effects (González-Suárez and Revilla  
353 2013). One important aspect of such complexity is that different populations may show starkly  
354 different responses to climate, and less severe demographic effects in one population may  
355 compensate for climate-related losses of individuals in another population (Schindler *et al.* 2015;  
356 Villellas *et al.* 2015). In addition, dispersal can stabilize decreasing populations and allow mammals  
357 to track new suitable habitats, and may itself be strongly mediated by climate (Parmesan and Yohe  
358 2003; Root 2003; Travis *et al.* 2013). However, these important spatial aspects of demographic  
359 complexity have thus far been rarely assessed, with only three of the 106 studies quantitatively  
360 linking dispersal (emigration or immigration), in addition to local survival or reproduction, to climate  
361 (Kreuzer and Huntly 2003; Ozgul *et al.* 2014; Wauters *et al.* 2004). Therefore, despite the  
362 challenges involved in collecting long-term demographic parameters, including dispersal, across  
363 the entire life cycle (Foden and Young 2016), the mechanistic insights gained from such parameters  
364 will be invaluable to understand the drivers of biodiversity loss under climate change (Travis *et al.*  
365 2013; Urban *et al.* 2016).

366  
367 In conclusion, our current mechanistic knowledge on mammal responses to climate change would  
368 benefit from strategic studies that fill the knowledge gaps identified here. Our take-home message  
369 echoes recent calls for more integrative climate-demography studies in bird populations (Zurell  
370 2017), along with numerous studies showing the benefits of such integrative research for evidence-  
371 based conservation (Møller *et al.* 2012). Other taxa, such as insects or amphibians, are far less  
372 well studied demographically than mammals or birds, but recent evidence suggests that  
373 demographic responses to climate change are complex and that understanding this complexity is  
374 key to conservation planning (Boggs 2016; Muths *et al.* 2017). Along with recent calls for a renewed

375 global effort to collect natural-history information (Urban *et al.* 2016), we therefore advocate for a  
376 coordinated effort to collect and model multiple demographic responses to climate across various  
377 taxa.

378

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390

### 391 **Data availability**

392 The data and R scripts that support the findings in this study are available Data and code available  
393 from the Dryad Digital Repository: <https://doi.org/10.5061/dryad.hmgqnk9g7> (Paniw *et al.*, 2021).

394

### 395 **Author Contributions**

396 MP, TDJ, GR, and RS-G devised the overall manuscript. MP and TDJ designed the literature review  
397 protocol, which was then implemented by MP, TDJ, GR, CRA, SL, AM, JC, NSG, JMB, and AP.  
398 The climatic data were derived by AC. The first draft of the manuscript was written by MP and  
399 RS-G, and all co-authors contributed to the final manuscript. See Table S1.2 for further specifics  
400 regarding task contributions.

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523 distribution models. *J Avian Biol* **48**: 1505-16.
- 524 **Supplementary Information** is available in the online version of the paper.

525

526 **Figure legends**

527

528 **Figure 1.** Global distribution of 106 mammal studies (grey points) that have assessed multiple  
529 demographic responses to climate across the species' life cycles. Point size indicates number of  
530 relationships between climatic drivers and age/stage-specific demographic rates (survival,  
531 development, and/or reproduction). Red-scale map background indicates projected climate-  
532 change vulnerability for the most biodiverse (G200) ecoregions, with redder colours indicating  
533 higher increase in extreme temperatures. Left insert shows number of demographic rates  
534 decreasing (-), not changing (0), or increasing (+) under increasing temperatures as function of  
535 ecoregion vulnerability. Shading on insert indicates total number of demographic rates linked to  
536 temperature per ecoregion vulnerability level.

537

538 **Figure 2.** Global distribution of mammals (points) with available information on climate-  
539 demography relationships. Point and bar colours indicate levels of threat assessment by the  
540 IUCN (No IUCN - species not assessed; No T - species assessed and currently faces no threats;  
541 No CT - climate change not considered a threat; CT - climate change considered a threat).  
542 Darker background on the map indicates higher mammal richness (number of species). Bottom-  
543 left insert displays the mean proportion of demographic rates per mammal population  $\pm$  S.E.  
544 (error bars) that may decrease under projected global climate change in different IUCN  
545 categories. Total number of populations with at least one decreasing rate per threat level are  
546 indicated above the bars. Species highlighted in Figure 4 are mapped here.

547

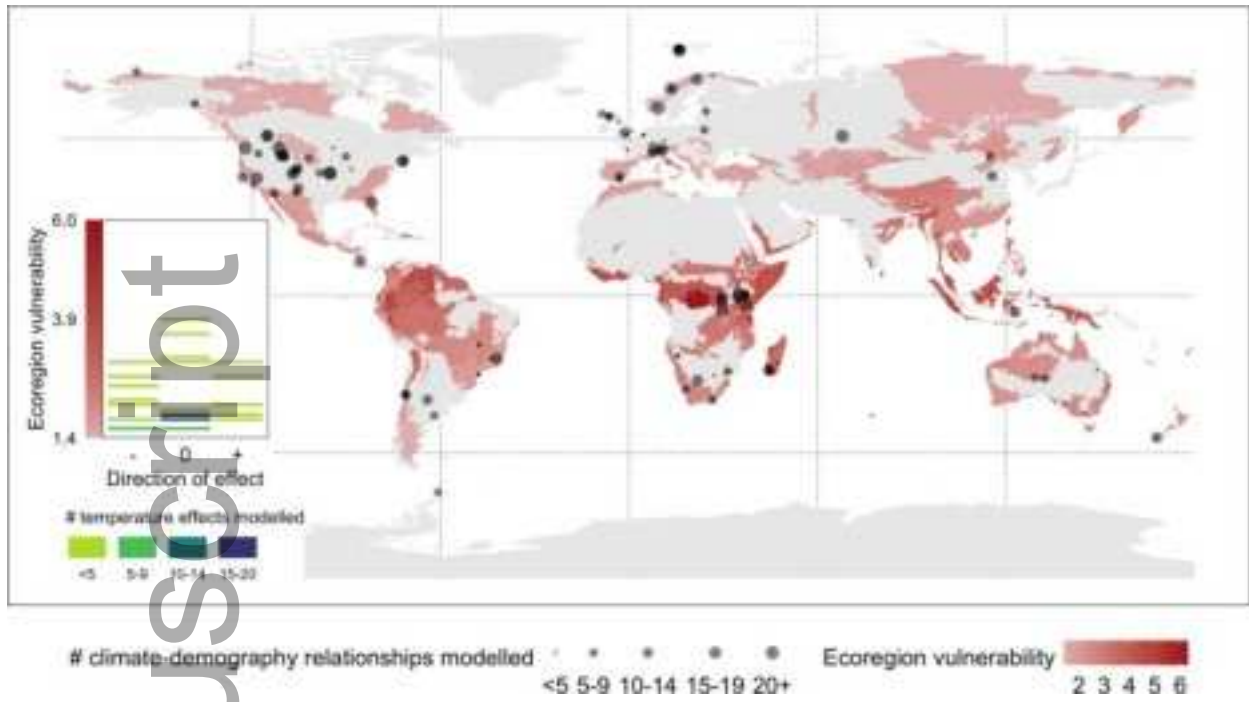
548 **Figure 3.** Summary potential demographic responses under projected global changes in  
549 temperature and precipitation across IUCN threat categories. Out of total number of populations  
550 reviewed per IUCN threat category (indicated next to bars), we show the proportion of  
551 populations where increasing or decreasing (+/-) responses to climate are projected for different  
552 ages/stages of the same demographic rate ("within"; e.g. pre-reproductive versus reproductive  
553 stage), or for different demographic rates ("among", e.g. survival versus reproduction). Categories  
554 include No IUCN - species not assessed; No T - species assessed and currently faces no threats;  
555 No CT - climate change is not considered a threat; CT - climate change is considered a threat.

556

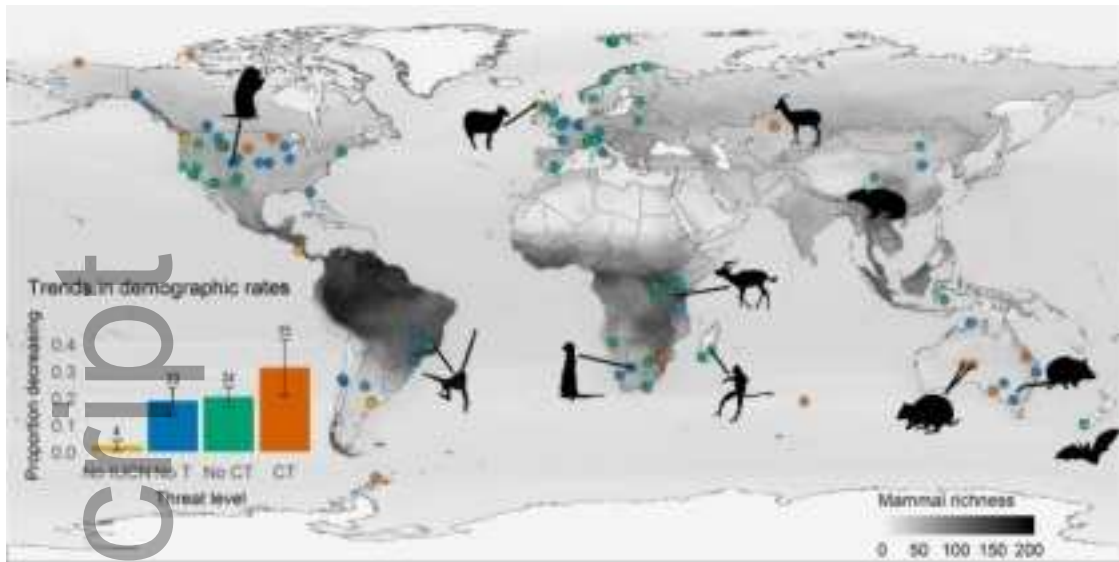
557 **Figure 4.** Detailed potential demographic responses to climate change for 11 example species.  
558 Demographic rates include survival (S), probability of reproducing and reproductive output (R),  
559 and growth and development (G), which can show only positive (+), only negative (-), context-  
560 dependent (CD; both positive and negative, depending on interactions with other drivers), or no  
561 (0) responses in the future. The number of instances that responses are recorded include all

562 stage-specific and climate driver-specific combinations. From top left to bottom right, the species  
563 include Soay sheep (*Ovis aries*), agile antechinus (*Antechinus agilis*), yellow-bellied marmot  
564 (*Marmota flaviventer*), meerkat (*Suricata suricatta*), pika (*Ochotona curzoniae*), long-tailed wattled  
565 bat (*Chalinolobus tuberculatus*), Milne-Edwards's sifaka (*Propithecus edwardsi*), northern muriqui  
566 (*Brachyteles hypoxanthus*), Saiga antelope (*Saiga tatarica*), impala (*Aepyceros melampus*), and  
567 black-flanked rock-wallaby (*Petrogale lateralis*).

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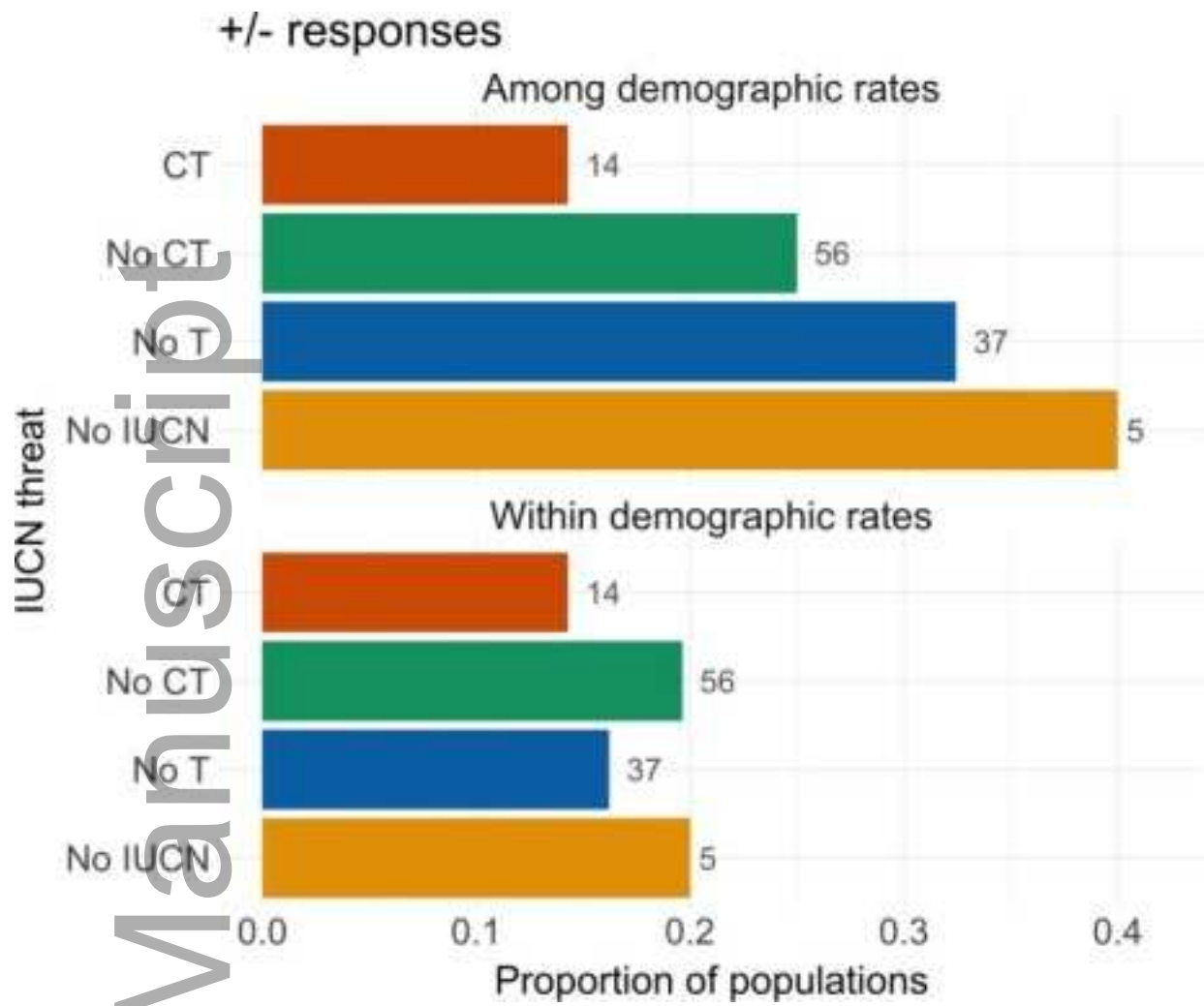


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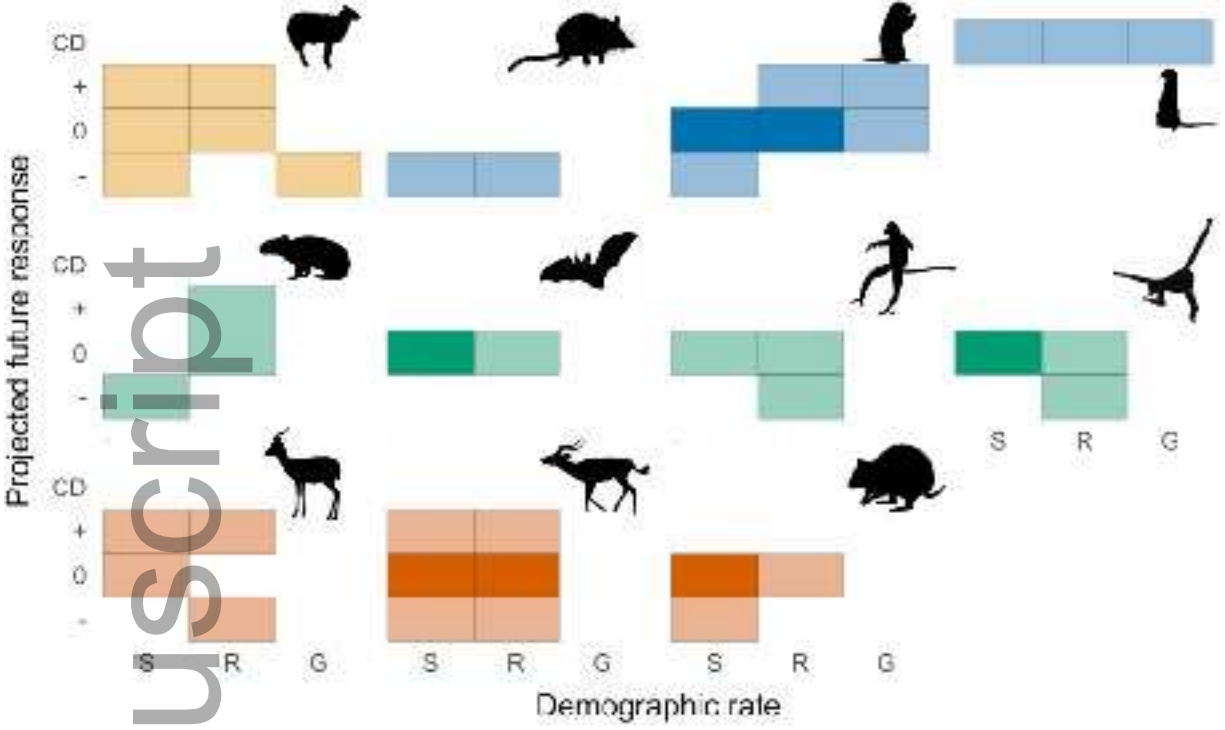


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# instances response recorded  
 ■ <10 ■ 10-20

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