

Global Patterns of Climate Change Impacts on Desert Bird Communities

Supplementary Tables

Supplementary Table 1 Parameter values for the microclimate model (“micro_terra” in NicheMapR) that define the desert habitat.

Parameter	Description	Value	Comment
REFL	Soil solar reflectance, decimal %	0.35	table 11.2 in Campbell and Norman (2012) ¹
Ushrht	Local height (m) at which air temperature, wind speed and humidity are to be computed for organism of interest	1.5	assumed that birds were sitting 1.5 m above ground
RUF	Roughness height (m), e.g. smooth desert is 0.0003, closely mowed grass may be 0.001, bare tilled soil 0.002-0.006, current allowed range: 0.00001 (snow) - 0.02 m.	0.0003	best estimate for deserts
CMH2O	Precipitable cm H2O in air column, 0.1 = very dry; 1.0 = moist air conditions; 2.0 = humid, tropical conditions (note this is for the whole atmospheric profile, not just near the ground)	0.5	best estimate for deserts

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32 **Supplementary Table 2 Parameter values used in the sensitivity analysis and percentage of**
 33 **safe sites that were defined as the 25% sites with the largest TEWL overlap between**
 34 **current years and future years (global mean temperatures are 2°C warmer than pre-**
 35 **industrial values) that were predicted.**

Parameter	Description	Value used for the model species	Lower value used and percent of safe sites predicted	Higher value used and percent of safe sites predicted
REFLD	feather reflectivity dorsal (fractional, 0-1)	0.25	0.1; 98.0%	0.5; 97.8%
REFLV	feather reflectivity ventral (fractional, 0-1)	0.43	0.1; 97.5%	0.5; 98.5%
TC_MAX	maximum core temperature (°C)	44	43; 97.8%	45; 98.0%
PANT_MULT	multiplier on basal metabolic rate at maximum panting level	1.01	1; 98.3%	2; 86.5%
PANT_MAX	maximum breathing rate multiplier to simulate panting	7.5	4; 97.0%	11; 95.5%
Usrhyt	Local height (m) at which air temperature, wind speed and humidity are to be computed for organism of interest (m)	1.5	0.3; 95.3%	NA
QBASAL	basal heat generation (W)	0.278*0.13*mass ^{0.713}	Different equation or assumption and percent of safe sites predicted	
Onset of panting		Start with the increase of body temperature	0.278*0.089*mass ^{0.724} ; 86%	Start after reaching maximum body temperature; 95.5%
			Percent of safe sites predicted	
	A combination of above parameter values that maximize the water loss rate (values in red)	NA	87.3%	
	A combination of above parameter values that minimize the water loss rate (values in blue)	NA	83.0%	

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47 **Supplementary Table 3 Parameter values used in the sensitivity analysis and percentage of**
 48 **safe sites that were defined as the 25% sites with the largest ADR overlap between current**
 49 **years and future years (global mean temperatures are 2°C warmer than pre-industrial**
 50 **values) that were predicted.**

Parameter	Description	Value used for the model species	Lower value used and percent of safe sites predicted	Higher value used and percent of safe sites predicted
REFLD	feather reflectivity dorsal (fractional, 0-1)	0.25	0.1; 94.5%	0.5; 91.0%
REFLV	feather reflectivity ventral (fractional, 0-1)	0.43	0.1; 91.8%	0.5; 95.3%
TC_MAX	maximum core temperature (°C)	44	43; 91.3%	45; 91.3%
PANT_MULT	multiplier on basal metabolic rate at maximum panting level	1.01	1; 94.5%	2; 88.0%
PANT_MAX	maximum breathing rate multiplier to simulate panting	7.5	4; 88.5%	11; 87.3%
Usrhyt	Local height (m) at which air temperature, wind speed and humidity are to be computed for organism of interest (m)	1.5	0.3; 87.8%	NA
QBASAL	basal heat generation (W)	0.278*0.13*mass ^{0.713}	Different equation or assumption and percent of safe sites predicted	
Onset of panting		Start with the increase of body temperature	0.278*0.089*mass ^{0.724} ; 82.3%	Start after reaching maximum body temperature; 88.0%
			Percent of safe sites predicted	
	A combination of above parameter values that maximize the water loss rate (values in red)	NA	77.3%	
	A combination of above parameter values that minimize the water loss rate (values in blue)	NA	69.3%	

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61 **Supplementary Table 4 Pearson Correlation Coefficient (estimated using a two-sided**
62 **Pearson Correlation test) and Weighted Jaccard Similarity for pairwise comparison**
63 **between metrics (Tair, TEWL and ADR) for estimating the climate-change impacts on**
64 **global warm deserts. Climate change impacts were estimated by overlapping estimated**
65 **area of kernel density estimations of current (1986-2015) and future values of Tair, TEWL**
66 **and ADR, respectively. We considered two behavior assumptions (the bird shifting between**
67 **open and shady areas to minimize their hourly water loss or always staying in the open)**
68 **and two climate change scenarios (global mean temperatures being 2°C or 4°C warmer**
69 **than pre-industrial values).**
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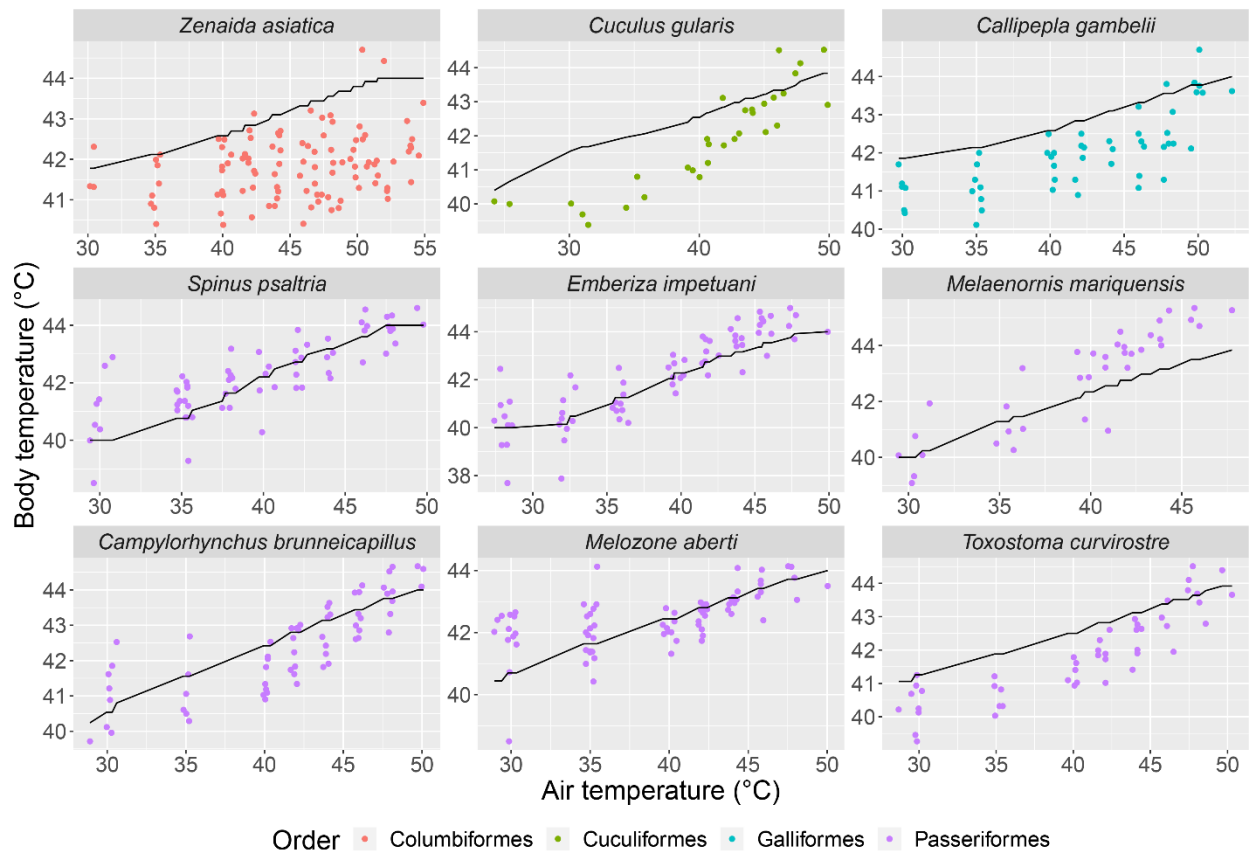
Result A	Result B	Behavior	Scenario	Correlation Coefficient	<i>P</i> value	Weighted Jaccard Index
Tair overlap	TEWL overlap	Shift	+2°C	0.818	0	68.6%
Tair overlap	ADR overlap	Shift	+2°C	0.799	0	75.5%
TEWL overlap	ADR overlap	Shift	+2°C	0.868	0	75.1%
Tair overlap	TEWL overlap	Open	+2°C	0.753	0	72.4%
Tair overlap	ADR overlap	Open	+2°C	0.657	0	72.1%
TEWL overlap	ADR overlap	Open	+2°C	0.886	0	78.1%
Tair overlap	TEWL overlap	Shift	+4°C	0.699	0	56.6%
Tair overlap	ADR overlap	Shift	+4°C	0.569	0	50.9%
TEWL overlap	ADR overlap	Shift	+4°C	0.867	0	62.8%
Tair overlap	TEWL overlap	Open	+4°C	0.863	0	48.9%
Tair overlap	ADR overlap	Open	+4°C	0.782	0	40.8%
TEWL overlap	ADR overlap	Open	+4°C	0.870	0	67.8%

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91 **Supplementary Table 5 Pearson Correlation Coefficient (estimated using a two-sided**
 92 **Pearson Correlation test) and Weighted Jaccard Similarity for pairwise comparison**
 93 **between physiological metrics (overlap between current and future values of TEWL /**
 94 **ADR) for estimating the climate-change impacts and mean current air temperature.**
 95 **Climate change impacts were estimated by overlapping estimated area of kernel density**
 96 **estimations of current (1986-2015) and future values of TEWL and ADR, respectively. We**
 97 **considered two behavior assumptions (the bird shifting between open and shady areas to**
 98 **minimize their hourly water loss or always staying in the open) and two climate change**
 99 **scenarios (global mean temperatures being 2°C or 4°C warmer than pre-industrial values).**
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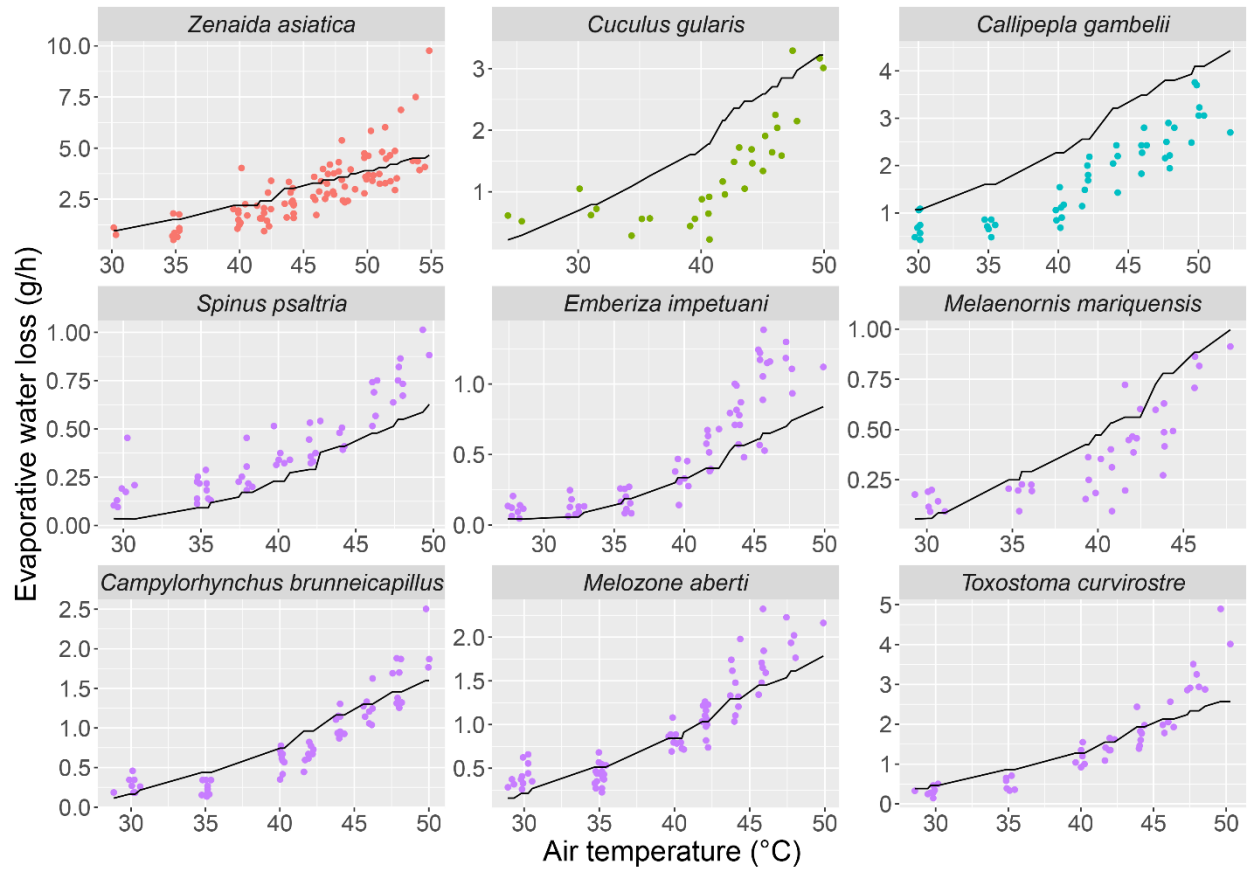
Result A	Result B	Behavior	Scenario	Correlation Coefficient	<i>P</i> value	Weighted Jaccard Index
Tair	TEWL overlap	Shift	+2°C	-0.468	0	36.8%
Tair	ADR overlap	Shift	+2°C	-0.378	8.488×10 ⁻²⁷¹	46.6%
Tair	TEWL overlap	Open	+2°C	-0.454	0	43.0%
Tair	ADR overlap	Open	+2°C	-0.427	0	51.4%
Tair	TEWL overlap	Shift	+4°C	-0.311	7.053×10 ⁻¹⁸¹	10.5%
Tair	ADR overlap	Shift	+4°C	-0.248	2.789×10 ⁻¹¹³	15.2%
Tair	TEWL overlap	Open	+4°C	-0.282	2.770×10 ⁻¹⁴⁷	17.6%
Tair	ADR overlap	Open	+4°C	-0.241	7.481×10 ⁻¹⁰⁷	16.5%

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 129 **Supplementary Figure 1** Core body temperature at a series of air temperatures in nine bird
 130 species from four orders and nine families (*Z. asiatica*, *C. gambelii*, *C. brunneicapillus* and *T.*
 131 *curvirostre* use desert habitat according to IUCN Red List). The points represent empirical
 132 values measured using a flow-through respirometry system (from literature) and the lines
 133 represent corresponding predicted values generated by the physiological model.

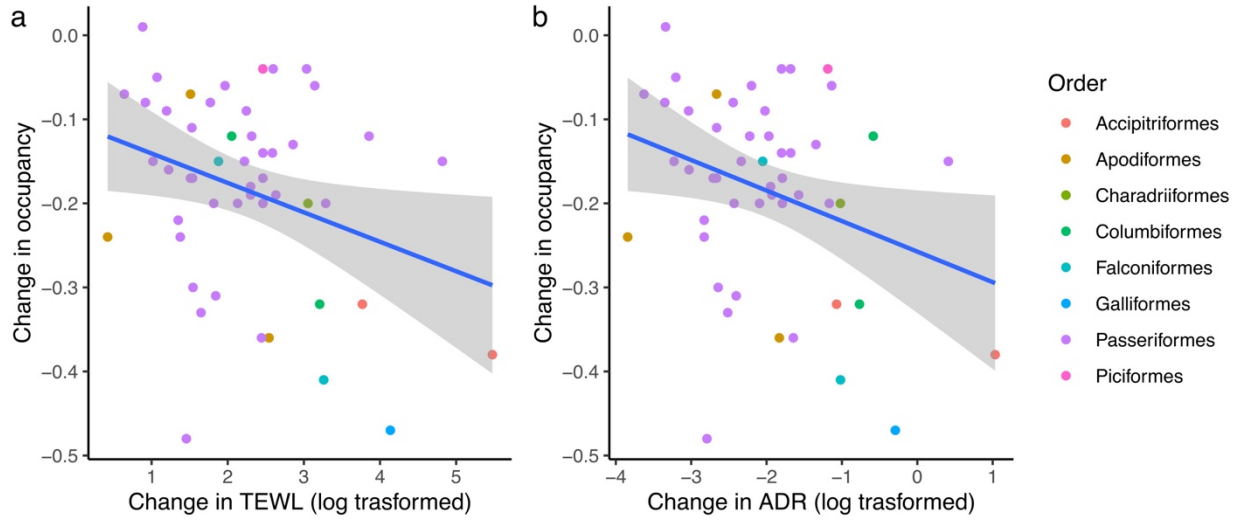
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Order • Columbiformes • Cuculiformes • Galliformes • Passeriformes

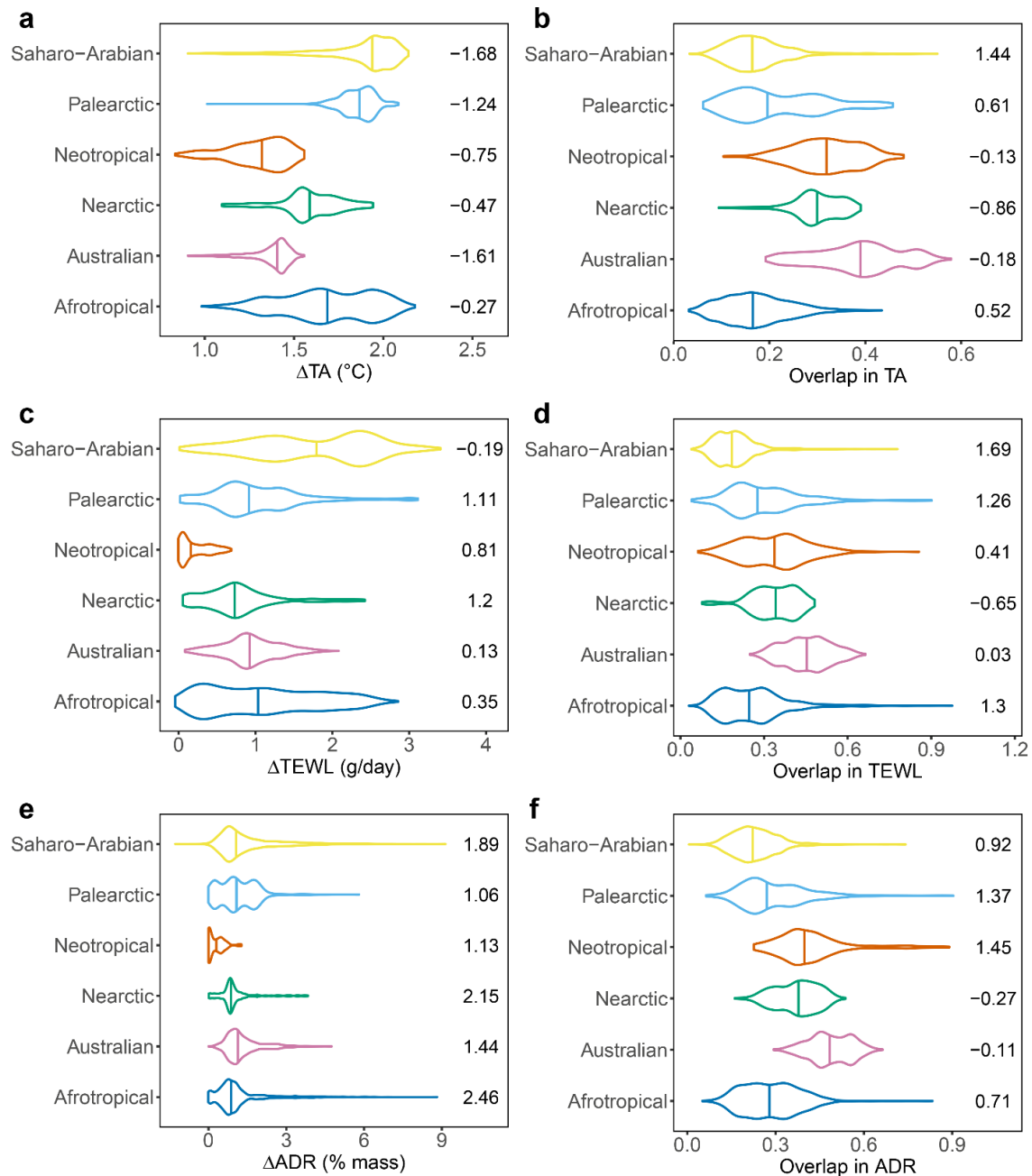
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Supplementary Figure 2 Evaporative water loss at a series of air temperatures in nine bird species from four orders and nine families (*Z. asiatica*, *C. gambelii*, *C. brunneicapillus* and *T. curvirostre* use desert habitat according to IUCN Red List). The points represent empirical values measured using a flow-through respirometry system (from literature) and the lines represent corresponding predicted values generated by the physiological model.



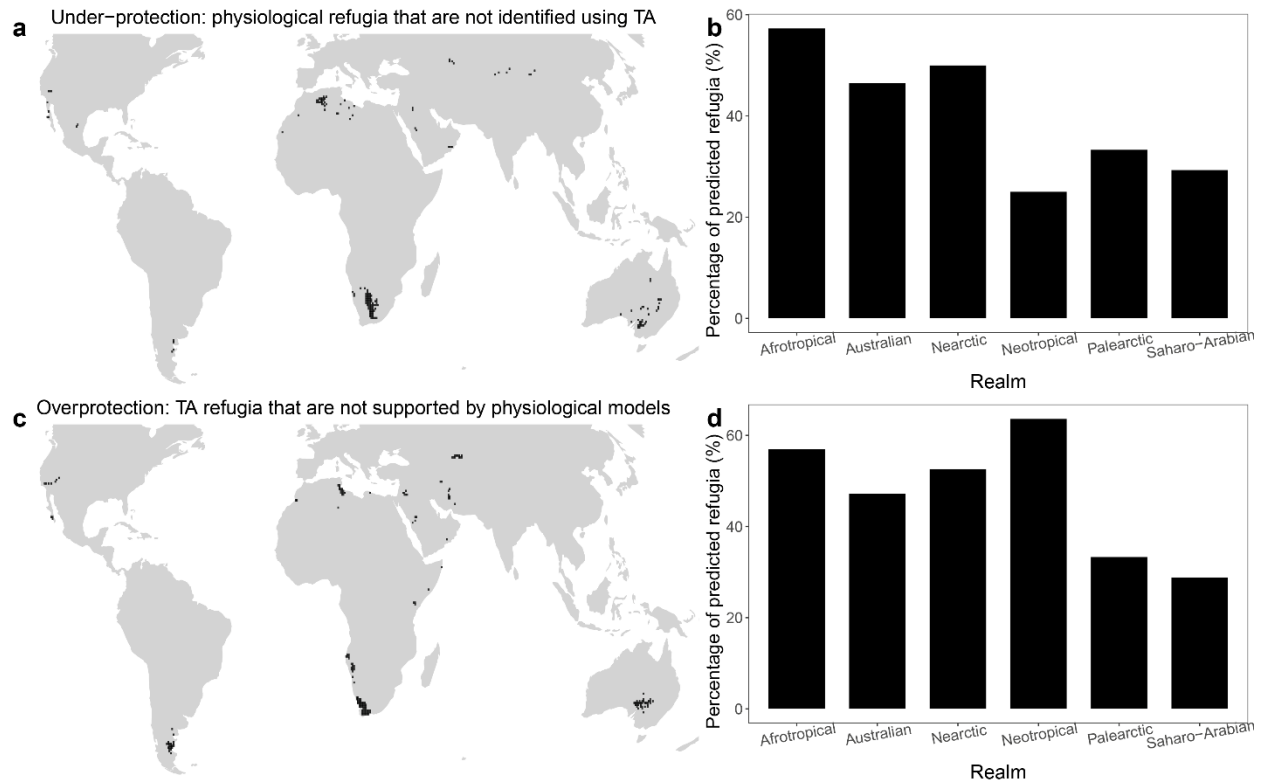
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Supplementary Figure 3 Predicted change in total evaporative water loss (g/day) of 50 bird species in the Mojave Desert and their changes in occupancy over the past century. The shaded areas around fitted lines represent the 95% confidence intervals.



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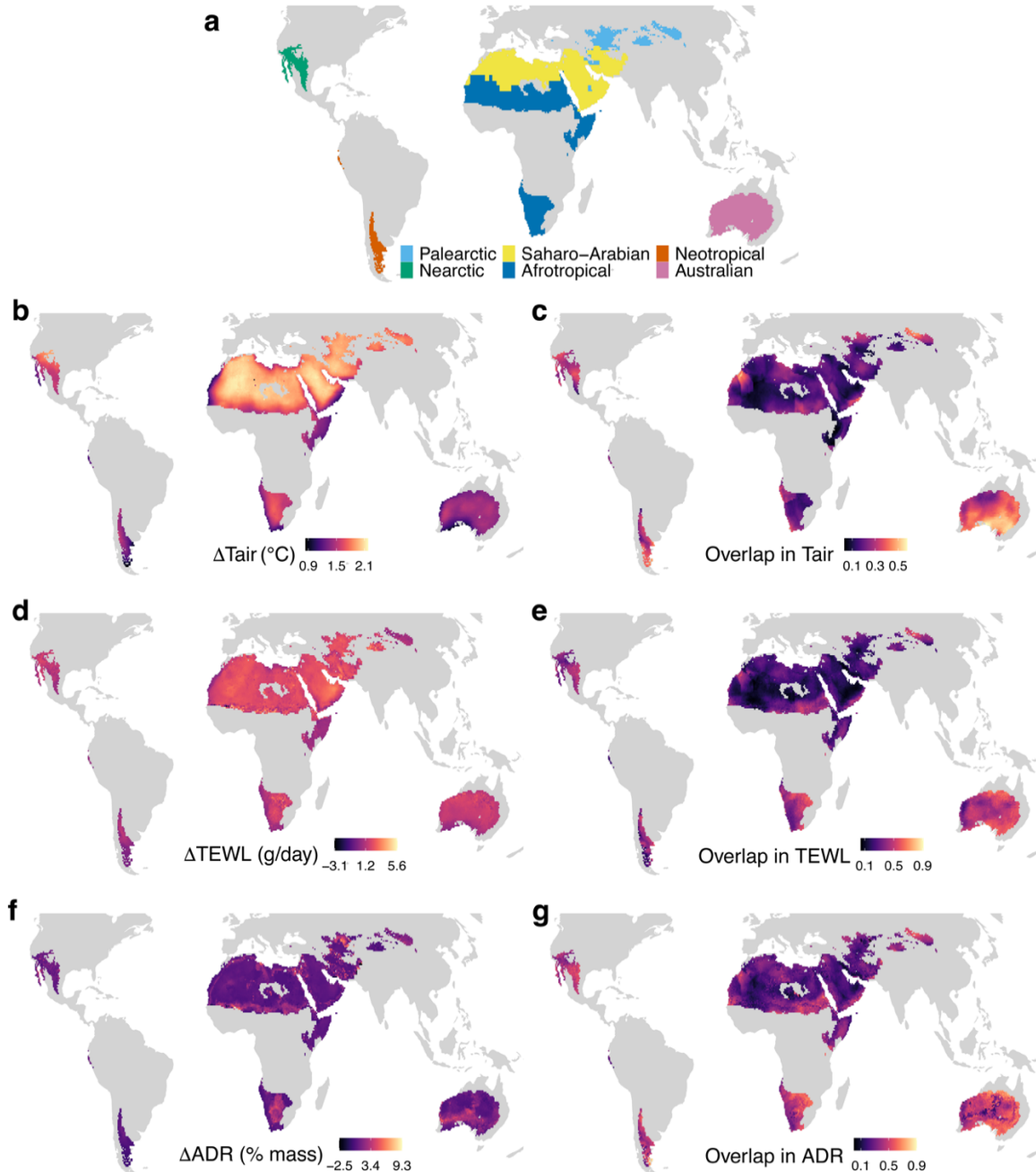
Supplementary Figure 4 Climate change impacts when global mean temperatures are 2°C warmer than pre-industrial values. The climate change impacts are estimated as the changes in (a, c and e; “ Δ ” represent value changes) and the overlap (b, d and f) between current and future values of mean air temperature (T_{air} ; $^{\circ}C$), total evaporative water loss (TEWL; g/day) and acute dehydration risk (ADR; %mass) during the hottest month (July for Northern Hemisphere, January for Southern Hemisphere) in global warm deserts. The violin plots show the probability distributions of realm-based values in corresponding to those metrics. The vertical line in each violin plot indicates the 50th percentile of the distribution. The numbers on the right of the violin plots indicate the skewness of the distribution (more positive values indicate positive [i.e., right] skewness). This figure assumed that the bird **actively shifts between open and shaded habitats** to minimize its water loss rate.



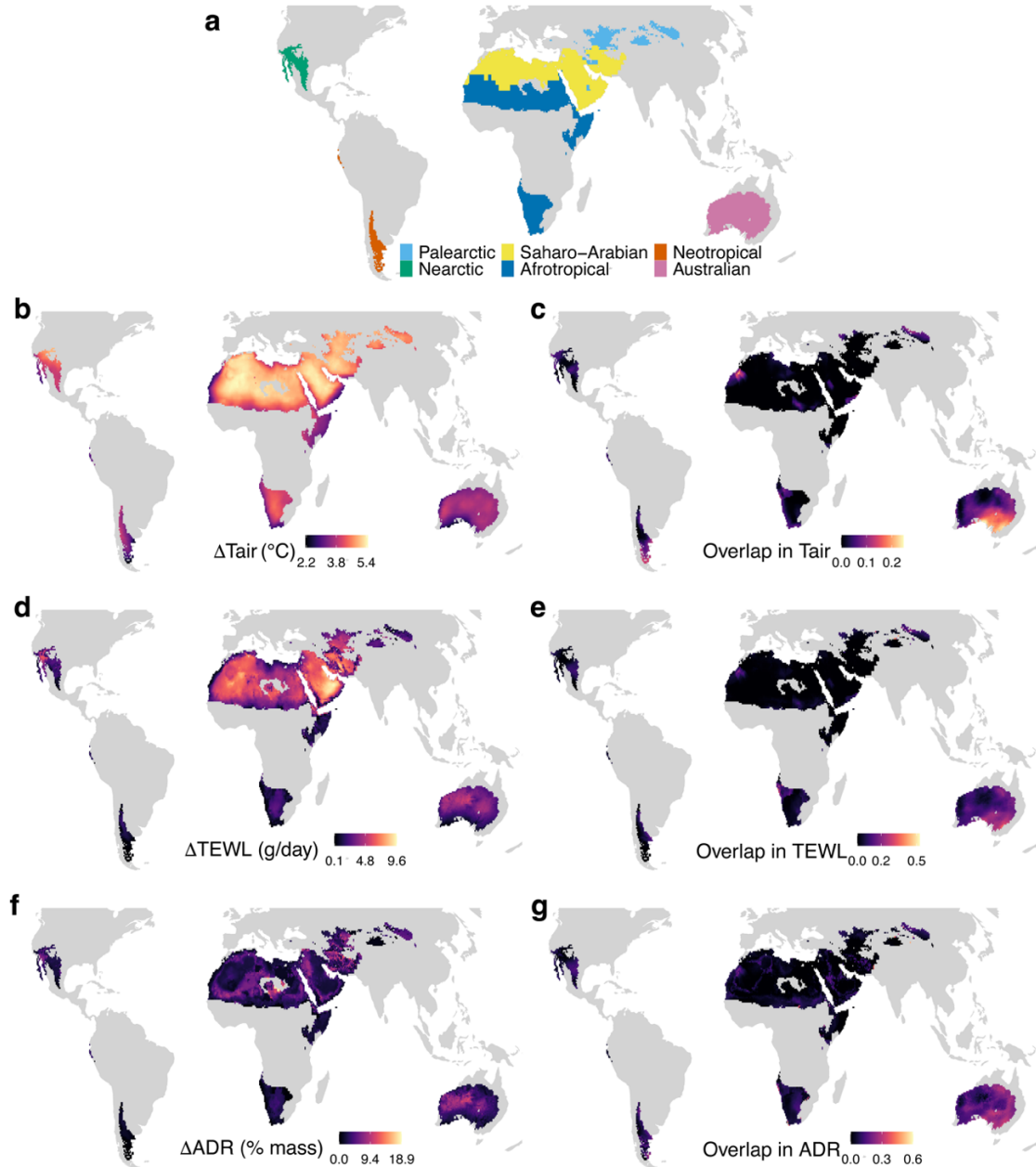
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217 **Supplementary Figure 5** Under-protection and overprotection when using air temperature as a
 218 proxy for physiological metric in identifying climate change refugia. The figure considers a
 219 climate change scenario that the global mean temperatures are 2°C warmer than pre-industrial
 220 values. Panel a shows areas identified as refugia using physiological metrics that are not
 221 identified as refugia using Tair (i.e., “under-protection”); panel c shows areas identified as
 222 refugia using Tair that are not identified as refugia using physiological metrics (i.e.,
 223 “overprotection”). Panel b and d show percentage of desert area in each desert realm where the
 224 “under-protection” and “overprotection” occurs, respectively. This figure assumed that the bird
 225 actively **shifts between open and shaded habitats** to minimize its water loss rate. See Fig. S15
 226 for results assuming the bird always stays at open habitat. See Fig. S16-17 for results for a
 227 scenario that the global mean temperatures are 4°C warmer than pre-industrial values.

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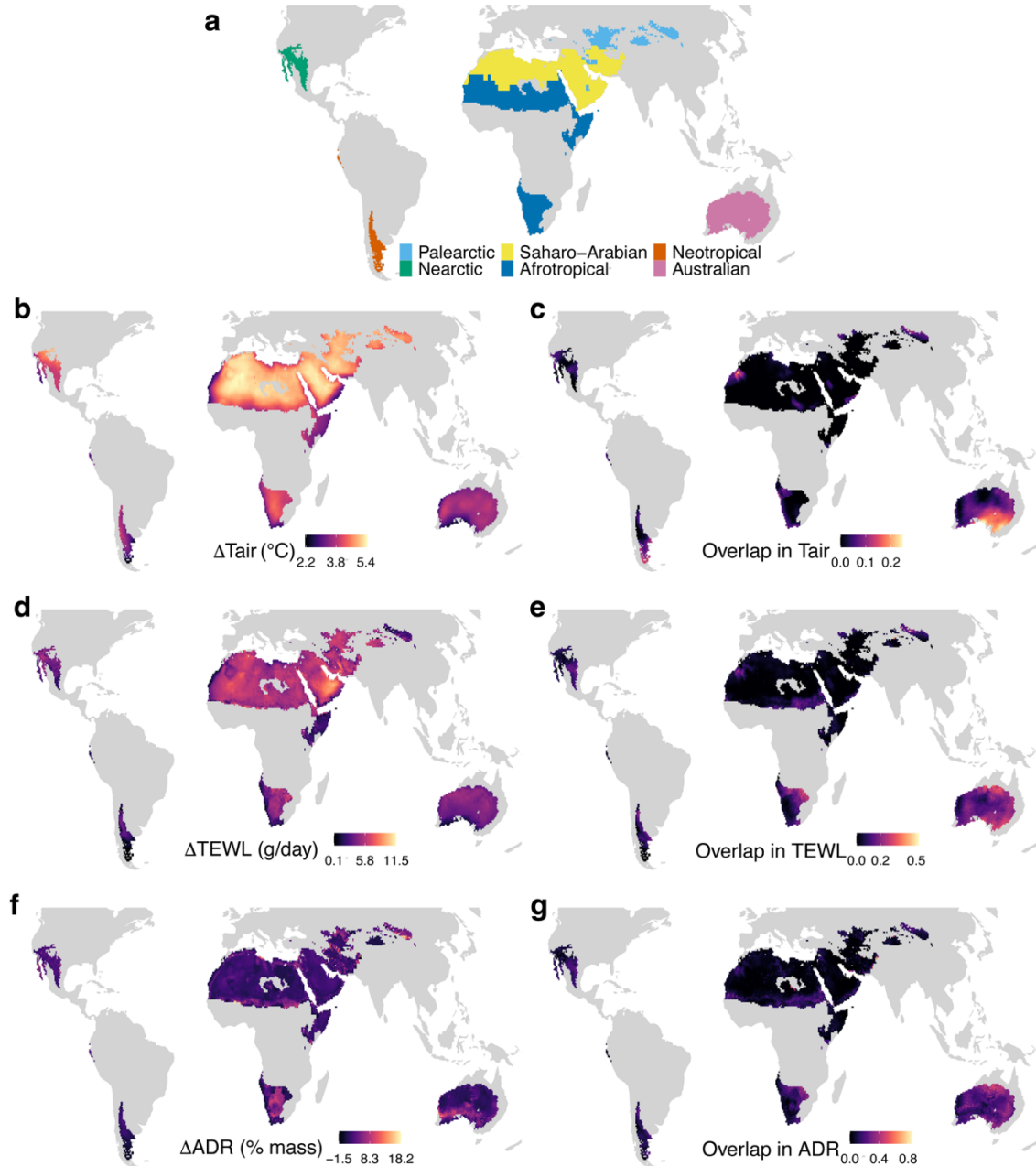


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 242 **Supplementary Figure 6** Climate change impacts for desert birds when global mean
 243 temperatures are 2°C warmer than pre-industrial values. The climate change impacts are shown
 244 as estimated changes in mean values (panels b, d, and f; “Δ” represent value changes; warmer
 245 colors indicate higher impact) and proportion of overlap between current and future values
 246 (panels c, e, and g; cooler colors indicate higher impact) of air temperature (Tair; °C), total
 247 evaporative water loss (TEWL; g/day) and acute dehydration risk (ADR; percent of body mass)
 248 during the hottest month (July for Northern Hemisphere, January for Southern Hemisphere).
 249 Panel a shows the locations of the six major realms containing warm deserts (“desert realms”)
 250 and desert birds (bird species having ≥ 90% of their habitat within warm deserts). This figure
 251 assumed that the bird always stays in **open habitat**.



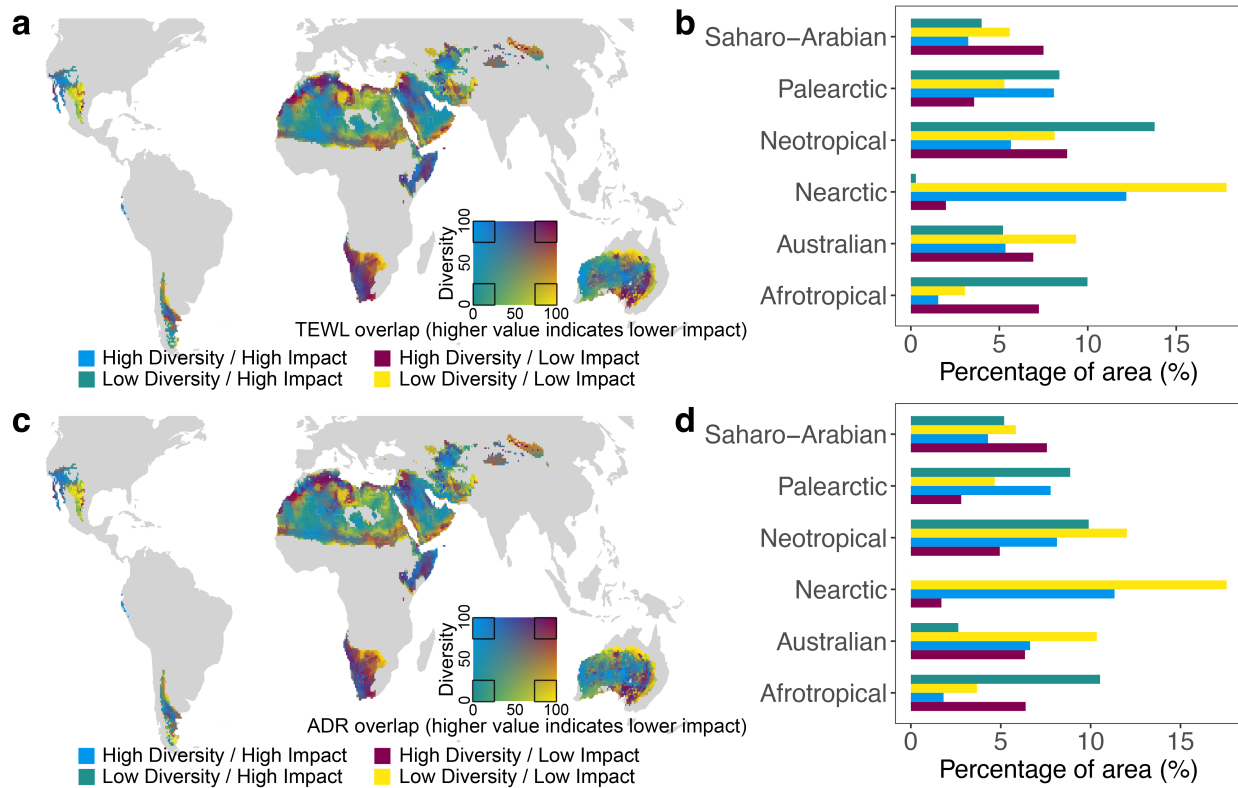
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253 **Supplementary Figure 7** Climate change impacts for desert birds when global mean
 254 temperatures are 4°C warmer than pre-industrial values. The climate change impacts are shown
 255 as estimated changes in mean values (panels b, d, and f; “Δ” represent value changes; warmer
 256 colors indicate higher impact) and proportion of overlap between current and future values
 257 (panels c, e, and g; cooler colors indicate higher impact) of air temperature (Tair; °C), total
 258 evaporative water loss (TEWL; g/day) and acute dehydration risk (ADR; percent of body mass)
 259 during the hottest month (July for Northern Hemisphere, January for Southern Hemisphere).
 260 Panel a shows the locations of the six major realms containing warm deserts (“desert realms”)
 261 and desert birds (bird species having ≥ 90% of their habitat within warm deserts). This figure
 262 assumed that the bird **actively shifts between open and shaded habitats** to minimize its water
 263 loss rate.



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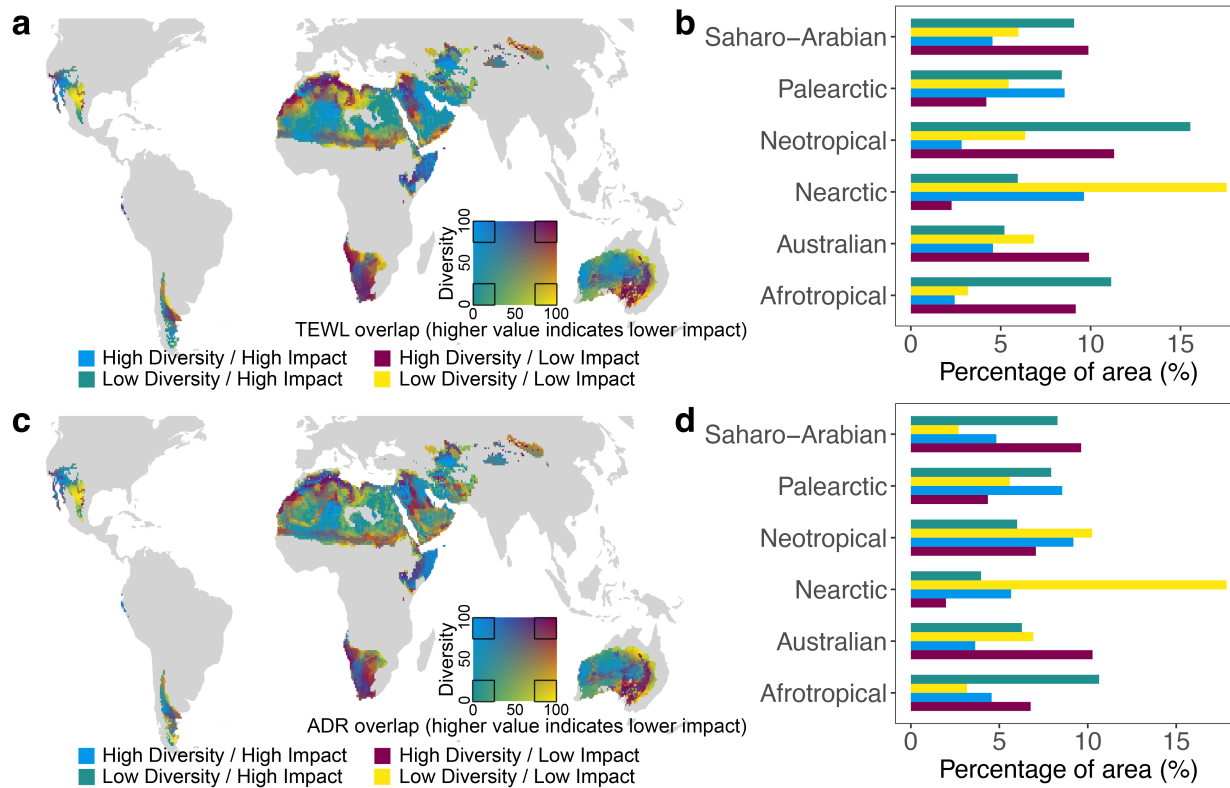
265 **Supplementary Figure 8** Climate change impacts for desert birds when global mean
 266 temperatures are 4°C warmer than pre-industrial values. The climate change impacts are shown
 267 as estimated changes in mean values (panels b, d, and f; “Δ” represent value changes; warmer
 268 colors indicate higher impact) and proportion of overlap between current and future values
 269 (panels c, e, and g; cooler colors indicate higher impact) of air temperature (T_{air}; °C), total
 270 evaporative water loss (TEWL; g/day) and acute dehydration risk (ADR; percent of body mass)
 271 during the hottest month (July for Northern Hemisphere, January for Southern Hemisphere).
 272 Panel a shows the locations of the six major realms containing warm deserts (“desert realms”)
 273 and desert birds (bird species having ≥ 90% of their habitat within warm deserts). This figure
 274 assumed that the bird always stays **open habitat**.



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276 **Supplementary Figure 9** Overlapping projections of climate change impacts and the
 277 distribution of desert bird diversity. Climate change impacts are measured as the proportion of
 278 overlap between current and future values of TEWL (panels a and b) or ADR (panels c and d)
 279 per pixel (higher overlap implies lower impact) when global mean temperatures are 2°C warmer
 280 than pre-industrial values. We defined desert bird as bird species with ≥ 90% area of their global
 281 habitat area falling within warm deserts. Diversity is calculated as rarity-weighted species
 282 richness, where species are weighted by the size of their global Area of Habitat (AOH). Panels a
 283 and c are bivariate heatmaps that place each pixel along axes of TEWL/ADR overlap and
 284 diversity value (from 0 to 100 percentiles; mapping is done for each desert realm).
 285 Correspondingly, panels b and d show the percentages of area in each desert realm falling within
 286 the four categories defined by TEWL/ADR overlap and diversity value (“High” and “Low” are
 287 defined by whether the pixel value falls in the top or bottom 25% of all pixel values within that
 288 desert realm, respectively). For each pixel, we averaged the results for birds in three body mass
 289 categories (see Methods), weighted by the number of bird species in each category, to calculate
 290 TEWL and ADR values. This figure assumed that the bird always stays in **open habitat**.

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300 **Supplementary Figure 10** Overlapping projections of climate change impacts and the
 301 distribution of desert bird diversity. Climate change impacts are measured as the proportion of
 302 overlap between current and future values of TEWL (panels a and b) or ADR (panels c and d)
 303 per pixel (higher overlap implies lower impact) when global mean temperatures are 4°C warmer
 304 than pre-industrial values. We defined desert bird as bird species with ≥ 90% area of their global
 305 habitat area falling within warm deserts. Diversity is calculated as rarity-weighted species
 306 richness, where species are weighted by the size of their global Area of Habitat (AOH). Panels a
 307 and c are bivariate heatmaps that place each pixel along axes of TEWL/ADR overlap and
 308 diversity value (from 0 to 100 percentiles; mapping is done for each desert realm).
 309 Correspondingly, panels b and d show the percentages of area in each desert realm falling within
 310 the four categories defined by TEWL/ADR overlap and diversity value (“High” and “Low” are
 311 defined by whether the pixel value falls in the top or bottom 25% of all pixel values within that
 312 desert realm, respectively). For each pixel, we averaged the results for birds in three body mass
 313 categories (see Methods), weighted by the number of bird species in each category, to calculate
 314 TEWL and ADR values. This figure assumed that the bird actively **shifts between open and**
 315 **shaded habitats** to minimize its water loss rate.

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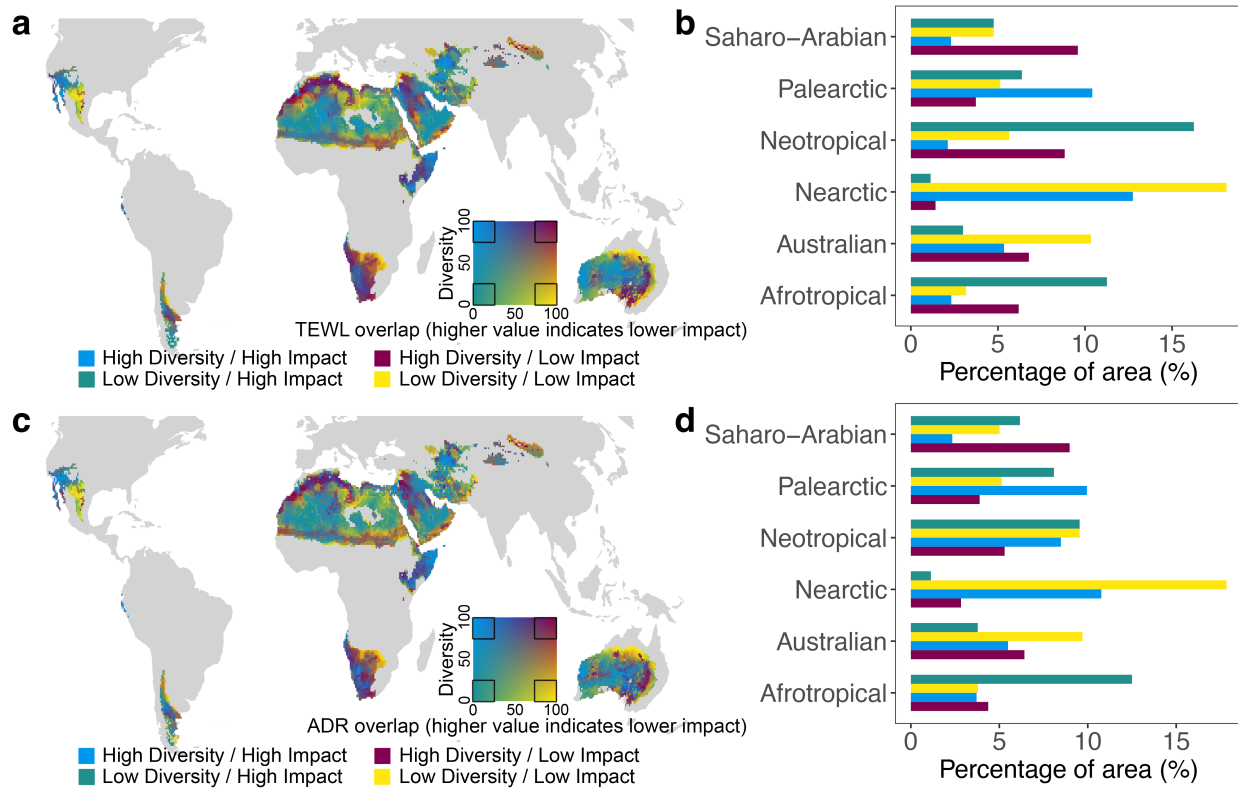
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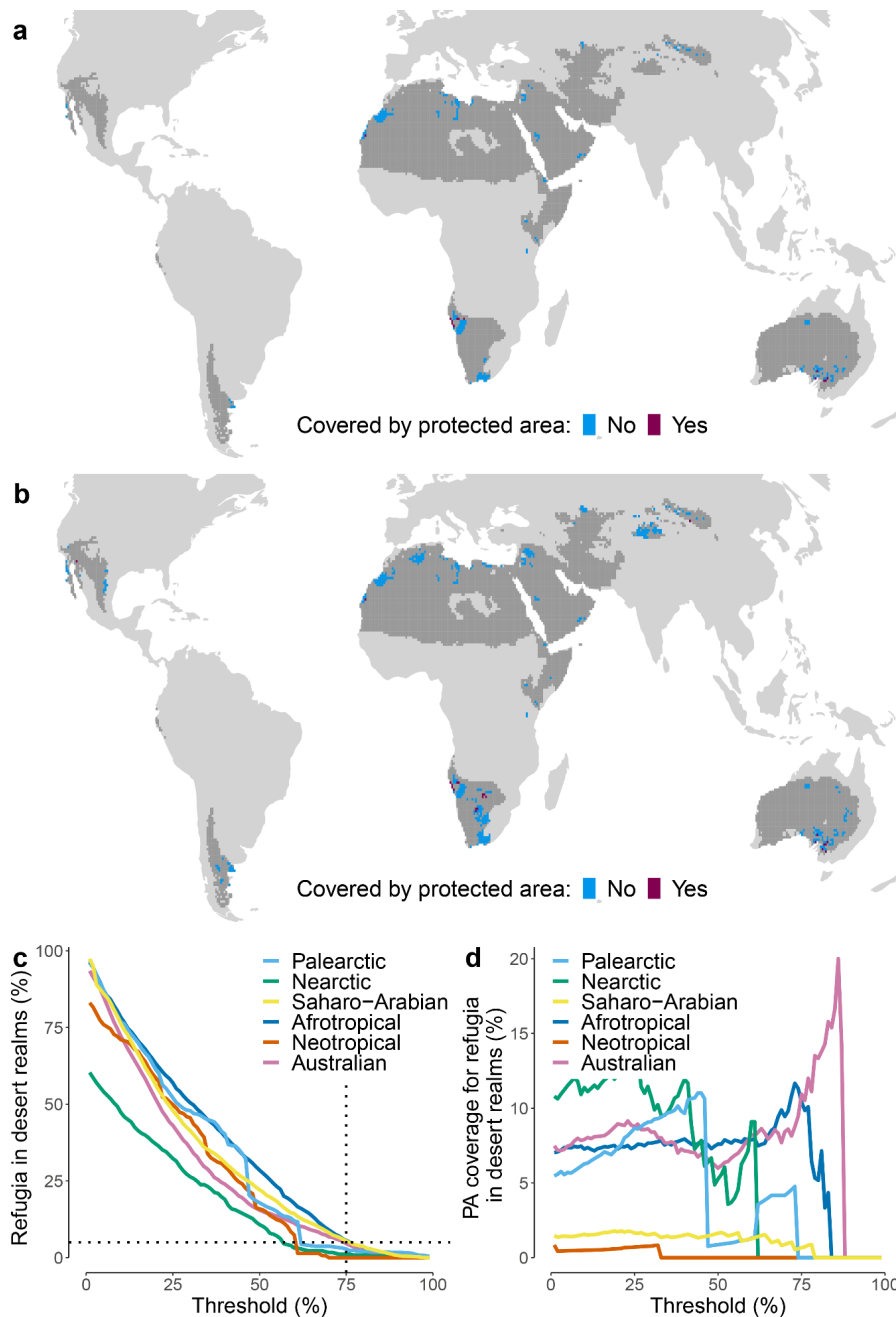
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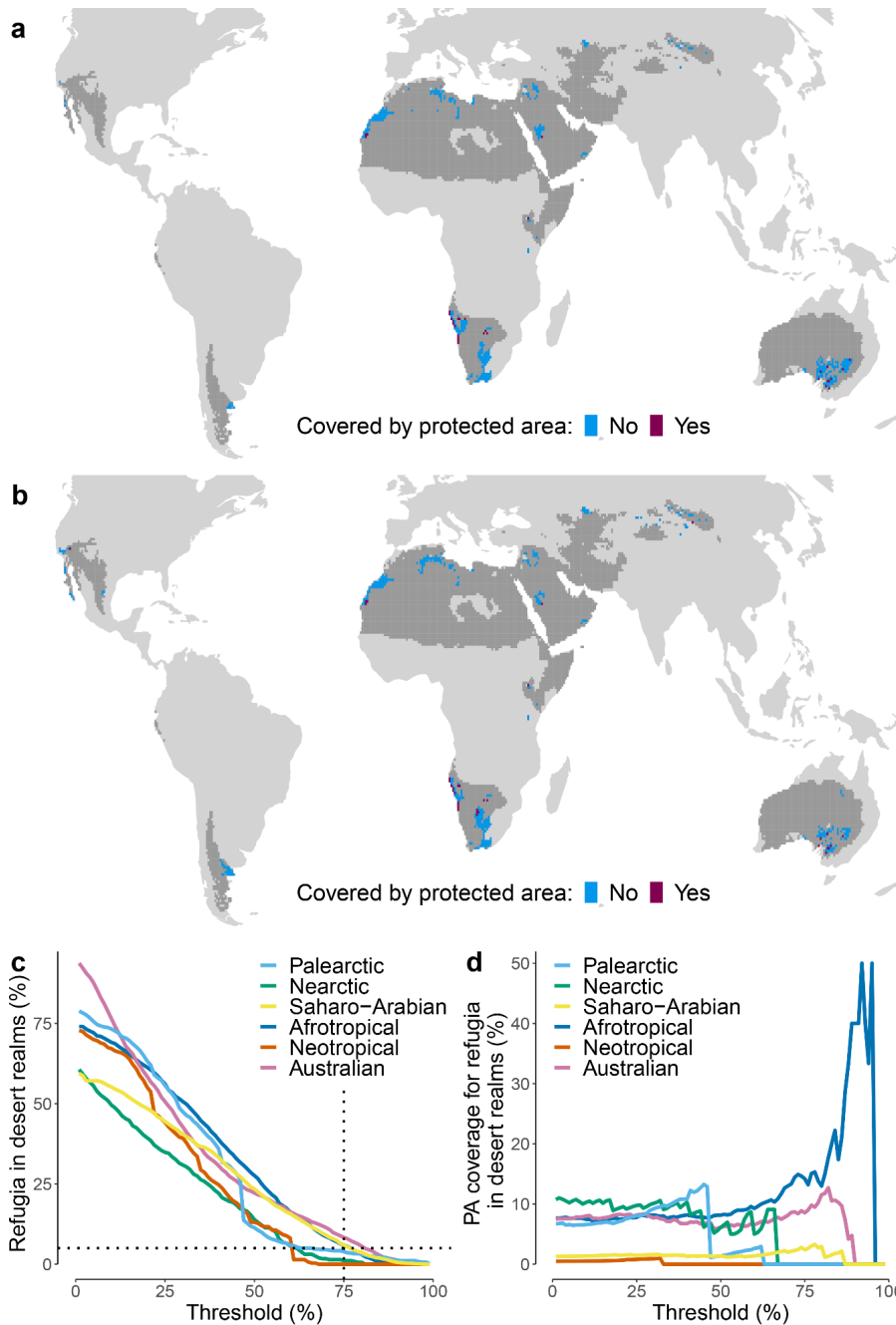
324 **Supplementary Figure 11** Overlapping projections of climate change impacts and the
 325 distribution of desert bird diversity. Climate change impacts are measured as the proportion of
 326 overlap between current and future values of TEWL (panels a and b) or ADR (panels c and d)
 327 per pixel (higher overlap implies lower impact) when global mean temperatures are 4°C warmer
 328 than pre-industrial values. We defined desert bird as bird species with ≥ 90% area of their global
 329 habitat area falling within warm deserts. Diversity is calculated as rarity-weighted species
 330 richness, where species are weighted by the size of their global Area of Habitat (AOH). Panels a
 331 and c are bivariate heatmaps that place each pixel along axes of TEWL/ADR overlap and
 332 diversity value (from 0 to 100 percentiles; mapping is done for each desert realm).
 333 Correspondingly, panels b and d show the percentages of area in each desert realm falling within
 334 the four categories defined by TEWL/ADR overlap and diversity value (“High” and “Low” are
 335 defined by whether the pixel value falls in the top or bottom 25% of all pixel values within that
 336 desert realm, respectively). For each pixel, we averaged the results for birds in three body mass
 337 categories (see Methods), weighted by the number of bird species in each category, to calculate
 338 TEWL and ADR values. This figure assumed that the bird always stays in **open habitat**.

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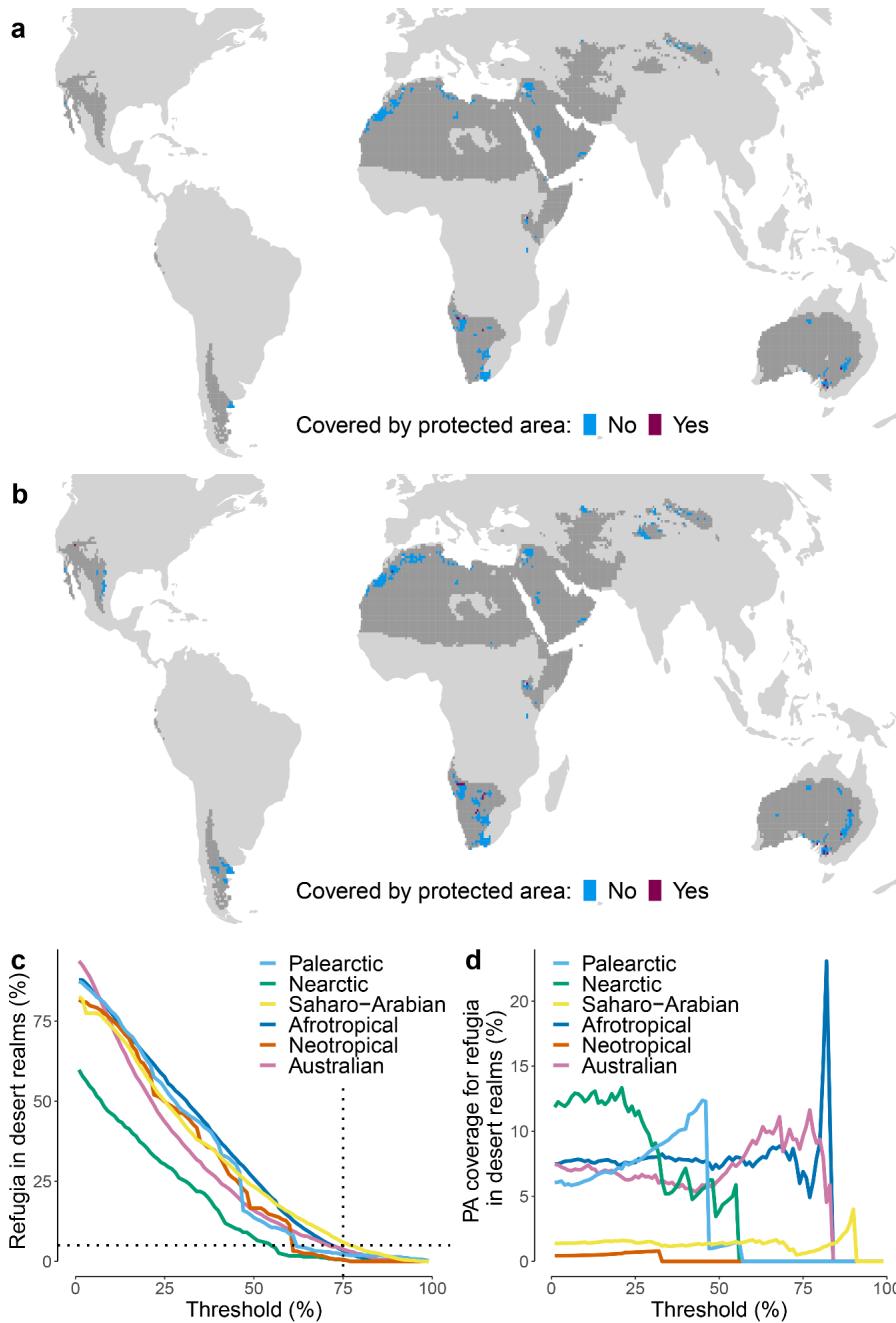
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348 **Supplementary Figure 12** Predicted locations of climate change refugia for desert birds in
 349 global warm deserts and their current protection status. The figure considers a climate change
 350 scenario that the global mean temperatures are 2°C warmer than pre-industrial values. Panel a
 351 shows the refugia identified using a fixed threshold of 75th percentile (i.e. top 25%) for ADR
 352 overlap, TEWL overlap, and avian diversity, while panel b shows the refugia identified using a
 353 floating threshold such that at least 5% of desert area in each realm is identified as refugia (see
 354 text for details). Panel c shows the relationship between the threshold used and the percentage of
 355 desert area in each realm identified as refugia. Panel d shows the relationship between the
 356 threshold used and PA coverage for refugia identified in each realm. This figure assumed that the
 357 bird always stays in **open habitat**.



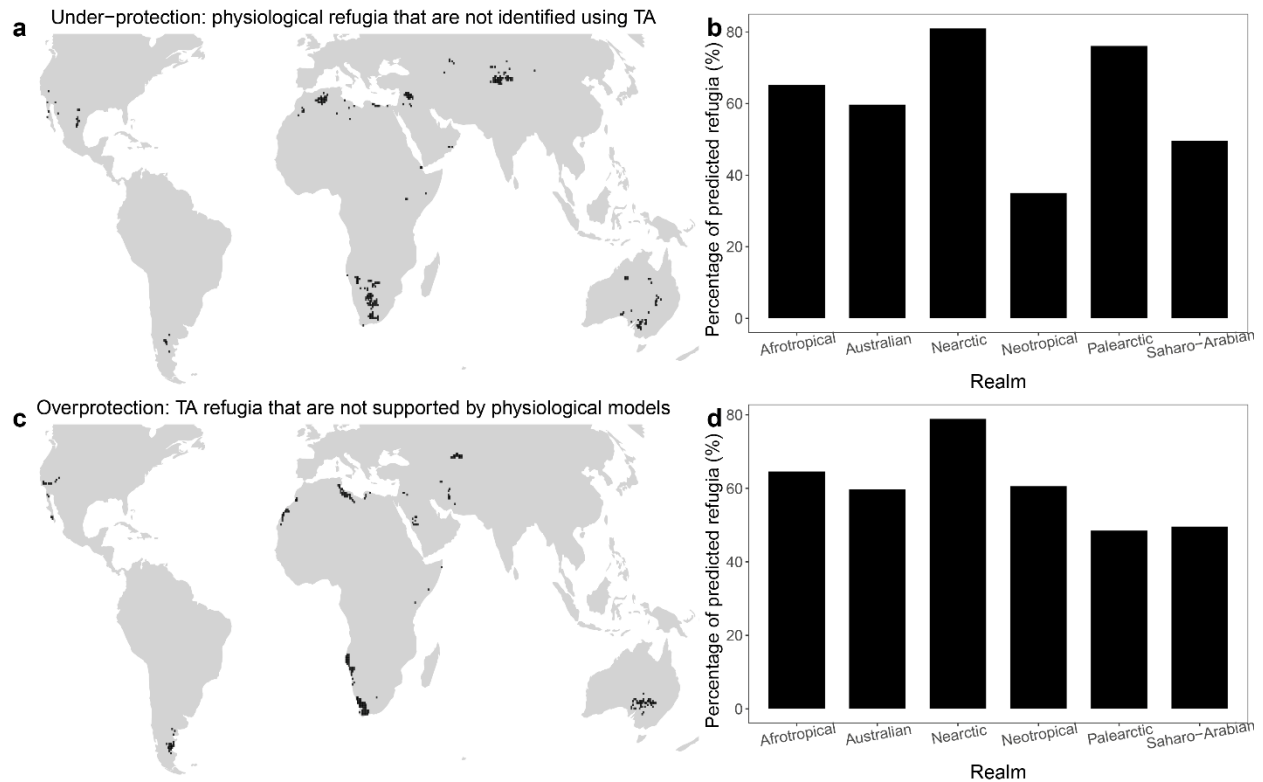
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359 **Supplementary Figure 13** Predicted locations of climate change refugia for desert birds in
 360 global warm deserts and their current protection status. The figure considers a climate change
 361 scenario that the global mean temperatures are 4°C warmer than pre-industrial values. Panel a
 362 shows the refugia identified using a fixed threshold of 75th percentile (i.e. top 25%) for ADR
 363 overlap, TEWL overlap, and avian diversity, while panel b shows the refugia identified using a
 364 floating threshold such that at least 5% of desert area in each realm is identified as refugia (see
 365 text for details). Panel c shows the relationship between the threshold used and the percentage of
 366 desert area in each realm identified as refugia. Panel d shows the relationship between the
 367 threshold used and PA coverage for refugia identified in each realm. This figure assumed that the
 368 bird actively **shifts between open and shaded habitats** to minimize its water loss rate.



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370 **Supplementary Figure 14** Predicted locations of climate change refugia for desert birds in
 371 global warm deserts and their current protection status. The figure considers a climate change
 372 scenario that the global mean temperatures are 4°C warmer than pre-industrial values. Panel a
 373 shows the refugia identified using a fixed threshold of 75th percentile (i.e. top 25%) for ADR
 374 overlap, TEWL overlap, and avian diversity, while panel b shows the refugia identified using a
 375 floating threshold such that at least 5% of desert area in each realm is identified as refugia (see
 376 text for details). Panel c shows the relationship between the threshold used and the percentage of
 377 desert area in each realm identified as refugia. Panel d shows the relationship between the
 378 threshold used and PA coverage for refugia identified in each realm. This figure assumed that the
 379 bird always stays in **open habitat**.



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381 **Supplementary Figure 15** Under-protection and overprotection when using air temperature as a
 382 proxy for physiological metric in identifying climate change refugia. The figure considers a
 383 climate change scenario that the global mean temperatures are 2°C warmer than pre-industrial
 384 values. Panel a shows areas identified as refugia using physiological metrics that are not
 385 identified as refugia using Tair (i.e., “under-protection”); panel c shows areas identified as
 386 refugia using Tair that are not identified as refugia using physiological metrics (i.e.,
 387 “overprotection”). Panel b and d show percentage of desert area in each desert realm where the
 388 “under-protection” and “overprotection” occurs, respectively. This figure assumed that the bird
 389 always stays in **open habitat**.

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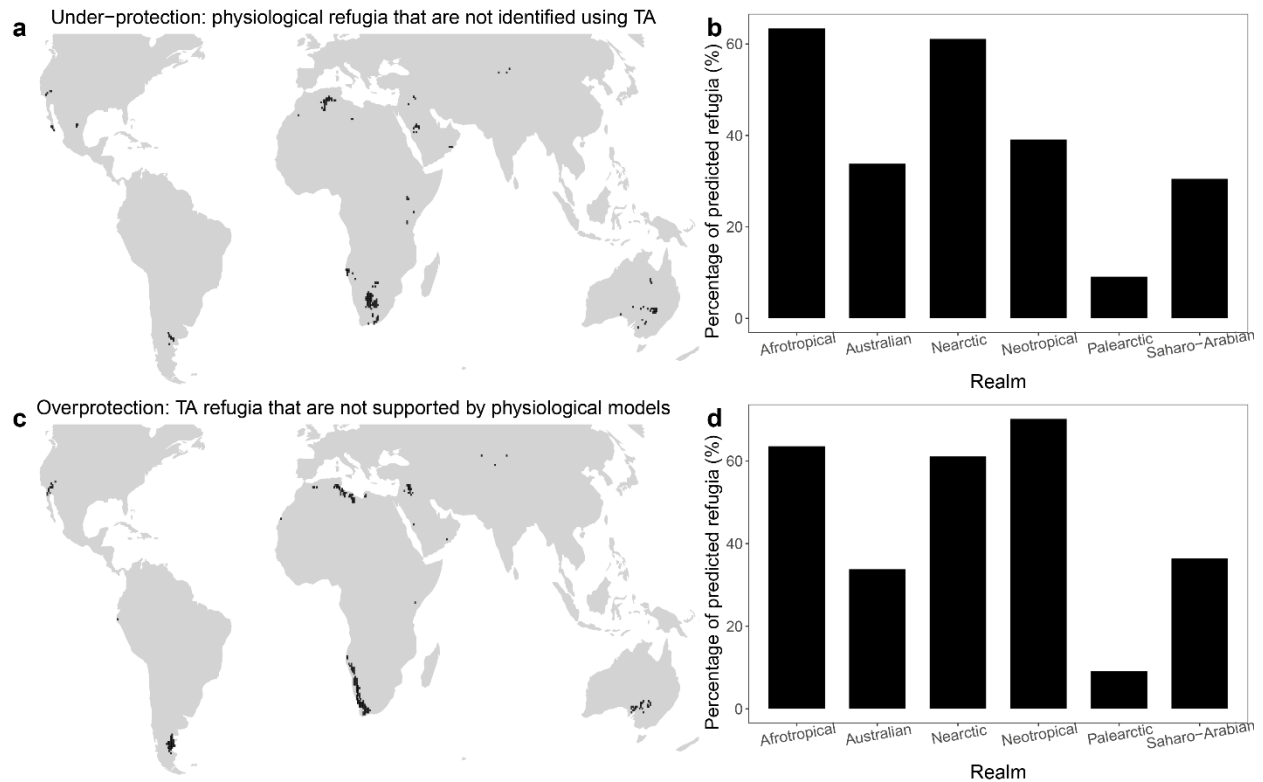
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406 **Supplementary Figure 16** Under-protection and overprotection when using air temperature as a
 407 proxy for physiological metric in identifying climate change refugia. The figure considers a
 408 climate change scenario that the global mean temperatures are 4°C warmer than pre-industrial
 409 values. Panel a shows areas identified as refugia using physiological metrics that are not
 410 identified as refugia using Tair (i.e., “under-protection”); panel c shows areas identified as
 411 refugia using Tair that are not identified as refugia using physiological metrics (i.e.,
 412 “overprotection”). Panel b and d show percentage of desert area in each desert realm where the
 413 “under-protection” and “overprotection” occurs, respectively. This figure assumed that the bird
 414 actively **shifts between open and shaded habitats** to minimize its water loss rate.

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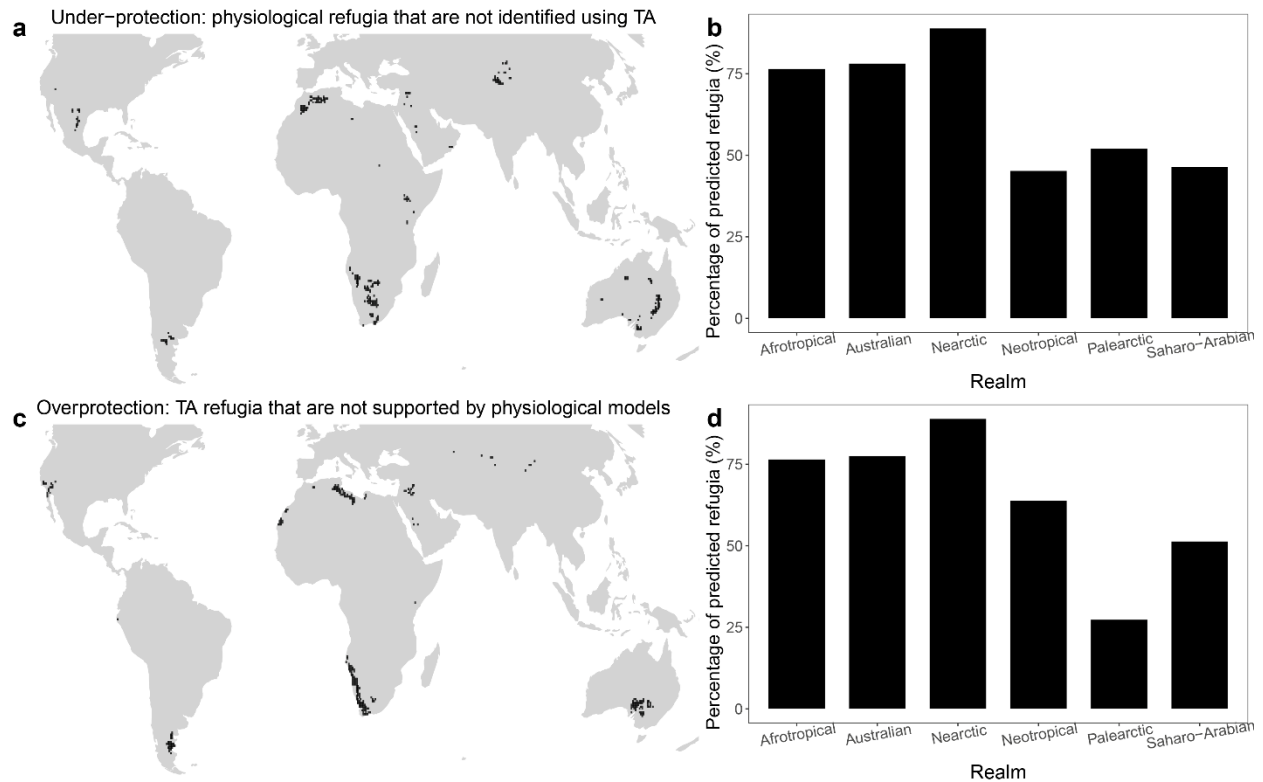
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431 **Supplementary Figure 17** Under-protection and overprotection when using air temperature as a
 432 proxy for physiological metric in identifying climate change refugia. The figure considers a
 433 climate change scenario that the global mean temperatures are 4°C warmer than pre-industrial
 434 values. Panel a shows areas identified as refugia using physiological metrics that are not
 435 identified as refugia using Tair (i.e., “under-protection”); panel c shows areas identified as
 436 refugia using Tair that are not identified as refugia using physiological metrics (i.e.,
 437 “overprotection”). Panel b and d show percentage of desert area in each desert realm where the
 438 “under-protection” and “overprotection” occurs, respectively. This figure assumed that the bird
 439 always stays in **open habitat**.

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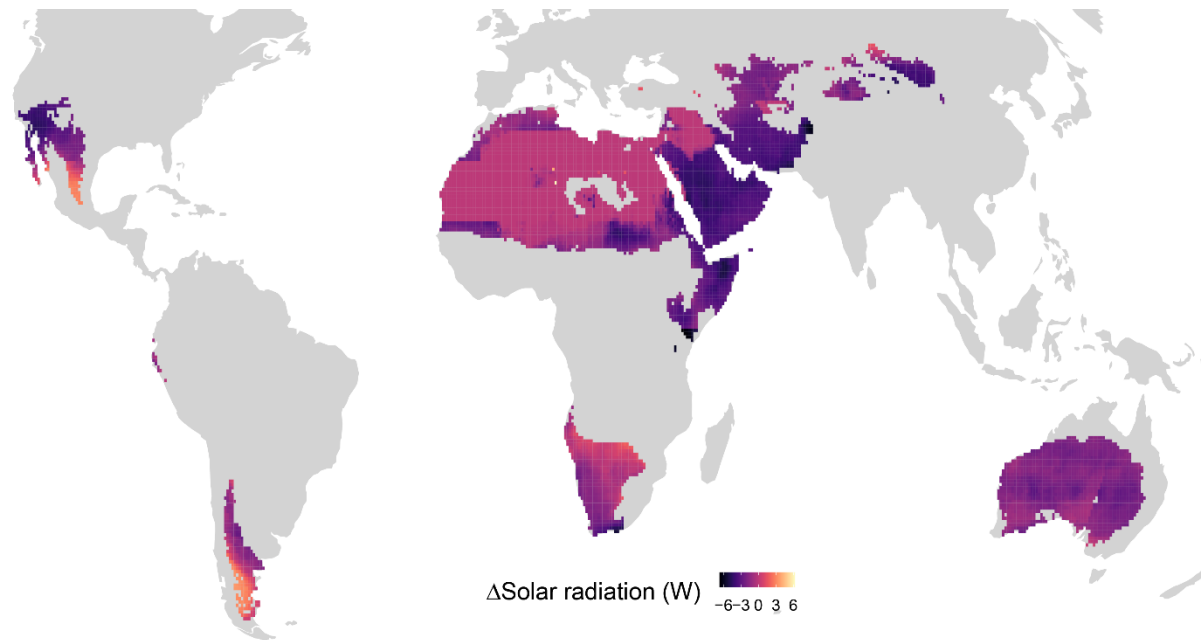
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456 **Supplementary Figure 18** Changes in mean solar radiation (W) during the hottest month (July
457 for Northern Hemisphere, January for Southern Hemisphere) in global warm deserts. “ Δ ”
458 represent value changes. The figure considers a climate change scenario that the global mean
459 temperatures are 2°C warmer than pre-industrial values.
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484 **Supplementary References**

485 1. Campbell, G. S. & Norman, J. *An introduction to environmental biophysics*. (Springer Science
486 & Business Media, 2012).

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