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Supplementary information

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Global hotspots of butterfly diversity are threatened in a warming world

In the format provided by the authors and unedited

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Supplementary Table 1 | Literature sources and data repositories of distribution data.

Title	Author & Year	Records	Access
Data repositories			
Butterfly species distribution models	Pinkert et al. (2025); this article	6,650 species	Single species maps: https://mol.org/species/; Dataset: https://doi.org/10.48600/56x3-dx56
Ant species richness and rarity	Kass et al. (2022)	14,324 (sub-) species	DataDryad:1748244; Files: ant_sp_richness_poly_msk.tif & ant_sp_rarity_poly_msk.tif (in results_species/richness_predictions_irs60K)
Plant species richness predictions	Kreft & Jetz, (2008)	>10.000 species	Available from authors upon request
Amphibians	IUCN.org and Birdlife International	6,437 species	iucnredlist.org/resources/spatial-data-download
Reptiles	Roll et al. (2017)	10,063 species	Available from authors upon request
Mammals	Marsh et al. (2022)	6,360 species	https://doi.org/10.48600/mol-48vz-p413
Birds	Jetz et al. (2012)	9,991 species	Available from authors upon request
Butterfly occurrence records			
Global Biodiversity Information Facility		10,661 species (>26 Mio. raw records)	GBIF.org (01 July 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.7radyr
Occasional photographic records of butterflies (Lepidoptera, Papilionoidea) in Cambodia. 1. The coastal Cardamom foothills (SW Cambodia), 2010-2018	Kosterin (2019a)	151 species (140 records)	Acta Biologica Sibirica 5(1):84-105. DOI: 10.14258/abs.v5.i1.5196
Occasional photographic records of butterflies (Lepidoptera, Hesperioidea and Papilionoidea) in Cambodia. 2. Ratanakiri and Mondulkiri Provinces of Eastern Cambodia, 2013-2018.	Kosterin (2019b)	118 species (216 records)	Acta Biologica Sibirica 5(4):21-37. DOI: 10.14258/abs.v5.i4.6816
The Butterflies of Iran and Iraq	Tshikolovets, Naderi & Eckweiler (2014)	412 species (11,483 records)	dd8f3af2-7bd6-460c-9ea0-f55fa5444015
The Butterflies of Thailand Vol. 1	Kimura, Aoki, Yamaguchi Uémura & Saito (2011)	342 species (3,381 records)	bf98e89a-6372-447d-b88e-8e3576b3f1c3
The Butterflies of Thailand Vol. 2	Kimura, Aoki, Yamaguchi Uémura & Saito (2014)	373 species (3,001 records)	1f59a825-4e54-456d-b621-2c7bea07eb37
Butterfly expert range maps			
Mariposas – Butterflies – Argentina	Klimaitis et al. (2018)	1189 species	eca9eec5-e2fd-4228-ad61-3a95d18544e3
Sequel to "The Life Histories of Asian Butterflies Vols. I & II"	Igarashi & Harada (2014)	194 species	f02f73d6-3ff5-4034-9094-1da6f91d24e9
The Life Histories of Asian Butterflies Vol. 1	Igarashi & Fukuda (1997)	299 species	32955004-1f1a-422d-b27f-975c88fc765c
The Life Histories of Asian Butterflies Vol. 2	Igarashi & Fukuda (2000)	380 species	142c08aa-7093-44cd-9ab8-d828e0643d7e
The complete field guide to butterflies of Australia	Braby (2016)	408 species	b37beb0e-9f6a-4e5d-a1f0-3163303ad1fa
Butterflies of Chile	Peña & Ugarte (1996)	165 species	822051c1-8543-43fa-b641-be3da923aab8
The Nymphalidae of China: Part I	Lang (2012)	423 species	ccf57b78-639f-4138-9662-2d1275e39f3d
An illustrated list of the Genus *Delias* Hübner of the world.	Yagishita, Nakano & Morita (1993)	107 species	6c08fa74-ab27-43a8-91d1-394296681a48
An illustrated checklist of the genus *Elymnias* Hübner, 1818 (Nymphalidae, Satyrinae)	Wei et al. (2017)	52 species	DOI: 10.3897/zookeys.676.12579

Butterflies of Britain and Europe	Tolman (2008)	411 species	fedd5e4d-d469-49ee-a58a-eb206a2afe02
Butterflies of the Fiji Islands	Prasad & Waqa-Sakiti (2007)	35 species	b522a6b2-ed14-4694-9708-2bf28d446260
Life histories of Korean butterflies	Kim & Ho (2012)	218 species	edf51b87-34ba-442b-b98b-5a080f00ded1
The Butterflies of Kyrgyzstan	Tshikolovets (2005)	274 species	3428f989-e644-45c5-9320-7d032fa498dc
The Butterflies of Ladak (N.-W. India)	Tshikolovets (2005)	87 species	f33371ca-1480-4387-a6e2-91f5fc933712
Butterflies of Mexico and Central America	Glassberg (2007)	1,594 species	f072f6ea-20ab-43c0-96f6-5edef46669db
The Butterflies of Mongolia	Tshikolovets (2009)	268 species	d08260ae-09b7-42c9-a597-3ee29874a59a
Kaufman field guide to butterflies of North America	Brock & Kaufman (2006)	607 species	8f316f82-7356-44ee-823d-8f830f241fab
New Zealand Butterflies	Gibbs (1980)	23 species	f2fc7933-fd26-41a2-846d-f3ed89a3973f
Guide to the Butterflies of the Palearctic Region, Nymphalidae part I, Tribe Argynnini: Argynnis, Issoria, Brenthis, Argyreus	Tuzov & Vozano (2003)	31 species	62f163d2-fff4-42c4-9a61-c55c62904817
Guide to the Butterflies of the Palearctic Region, Nymphalidae part II, Tribe Argynnini: Boloria, Proclossiana, Clossiana	Tuzov & Vozano (2006)	39 species	25cef51d-ab01-4390-86de-e03e2f3f7ea3
Guide to the Butterflies of the Palearctic Region, Nymphalidae part III. Subfamily Limenitidinae. Tribe Neptini	Bozano (2008)	53 species	88b436d9-9941-4d19-99bc-2644d046950e
Guide to the Butterflies of the Palearctic Region, Nymphalidae part VI, Family Limenitidinae, Tribes Limenitidini and Chalingini	Gallo & Della Bruna (2013)	37 species	05d432ad-3c74-477d-95f9-f048ed47332f
Guide to the Butterflies of the Palearctic Region, Satyrinae part V, Tribe Satyrini: Satyrus, Minois, Hipparchia	Sbordoni et al. (2018)	53 species	89229591-6e24-4787-ac3b-034bf8795bde
Butterflies of the South East Asian Islands, Volume I: Papilionidae	Tsukada & Nishiyama (1982)	123 species	ff1ef946-95b5-46d4-b9f2-9918a62918fe
Butterflies of the South East Asian Islands, Volume II: Pieridae and Danaidae	Yata & Morishita (1985)	235 species	049d0544-50b3-4408-8941-f6988c72f6e5
Butterflies of the South East Asian Islands, Volume III: Satyridae, Amathusiidae & Libytheidae	Aoki, et al. (1982)	214 species	dd9fe10d-c191-49d3-83e6-ea8134646072
Butterflies of the South East Asian Islands, Vol. IV: Nymphalidae	Tsukada (1985)	194 species	e0f7ad44-375b-4c4f-bae6-c31401a6f57a
Butterflies of the South East Asian Islands, Vol. V: Nymphalidae	Tsukada (1991)	160 species	d73946d2-9ad1-480d-b26b-4afec6052266
The butterflies of Russia: classification, genitalia, keys for identification (Lepidoptera: Hesperioidea and Papilionoidea)	Gorbunov (2001)	469 species	afabd30f-96cd-460f-82a1-7197f83e2d9e
Butterflies of Eastern Europe, Urals and Caucasus	Tshikolovets (2003)	291 species	fe4b9fd2-7da6-46b8-8bef-754044461210
Butterflies of South Africa	Woodhall (2005)	652 species	79361741-0668-4e77-933c-1eac68316fd9
The Butterflies of Altai, Sayans and Tuva (South Siberia)	Tshikolovets et al. (2009)	243 species	08653f6b-4204-4ac3-84a8-68ac2b52a4e4
The Butterflies of Tajikistan	Tshikolovets (2003)	281 species	531b17f2-4185-4d32-b95b-a2c5a3863e53
Butterflies of Transbaikal Siberia	Tshikolovets (2002)	214 species	269074a8-8a8b-4ad4-9896-6639085a3207
The Butterflies of Caucasus and Transcaucasia (Armenia, Azerbaijan, Georgia, and Russian Federation)	Tshikolovets (2012)	291 species	c26746e9-a77c-4caa-a74e-b5dc1608690d

Supplementary Table 2 | Dissimilarity in species composition of biogeographical realms. Dissimilarities were calculated using Chao's dissimilarity index based on the aggregated number of grids per species and biogeographical realm. Sample sizes (*n*, i.e. grids) per realm: Afrotropic = 1,901; Australasia = 1,182; Indomalayan = 977; Nearctic = 2,023; Neotropic = 1,873; Palearctic = 4,559.

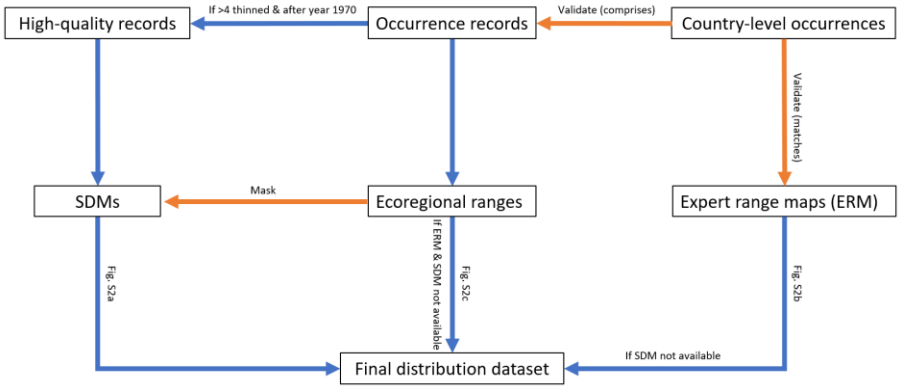
	Afrotropic	Australasia	Indomalayan	Nearctic	Neotropic	Oceania
Afrotropic						
Australasia	0.949					
Indomalayan	0.955	0.731				
Nearctic	0.992	0.987	0.988			
Neotropic	0.947	0.993	0.993	0.735		
Oceania	0.976	0.878	0.952	0.970	0.989	
Palearctic	0.952	0.957	0.741	0.882	0.994	0.966

Supplementary Table 3 | Fine-grain variation in warming for hotspots and non-hotspots. We quantify the fine-grain variation in projected difference in annual temperature (current – RCP 8.5 ensemble) for hotspot and non-hotspot areas. Fine-grain variations are calculated as the coefficient of variation of 1 km-resolution temperature records within 110 km-resolution grid cells (*n* = 12,515 grids). Shown are median values per diversity aspect, their difference, and rank-biserial correlation coefficients from Mann-Whitney (M-W; two-sided) tests that account for differences in the number of hotspots and their respective non-hotspots (all significant at $p < 0.001$).

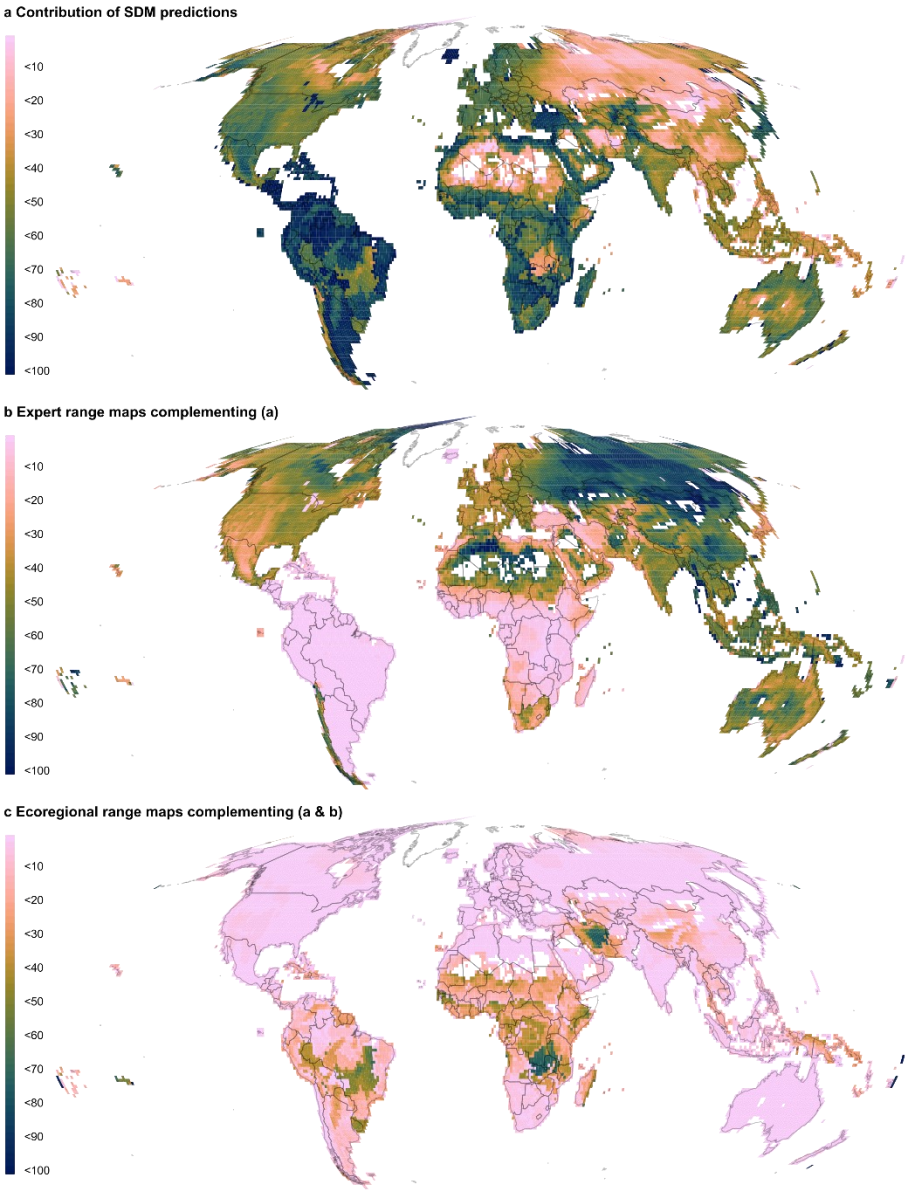
Diversity aspect	Hotspot	Non-hotspot	Difference	M-W coefficient
Species richness	0.007	0.008	–0.001	0.049
Range rarity	0.009	0.008	0.001	0.044
Phylogenetic diversity	0.007	0.008	–0.001	0.046

Supplementary Table 4 | Loss of current temperature niches for hotspots and non-hotspots under projected global warming. Median percentage of projected niche loss of current temperatures in species richness (SR), range rarity (RR) and phylogenetic diversity (PD) hotspots and their respective non-hotspots of six biogeographical realms (each *n* = 121,000 samples). Niche loss estimates are based on 10 km-resolution current condition temperature records and projected future temperatures under an ensemble model for the scenario RCP 8.5 to propagate microclimatic variation. For corresponding 110 km-resolution results see main text Extended Data Fig. 2. Hotspot locations are shown in Fig. 2.

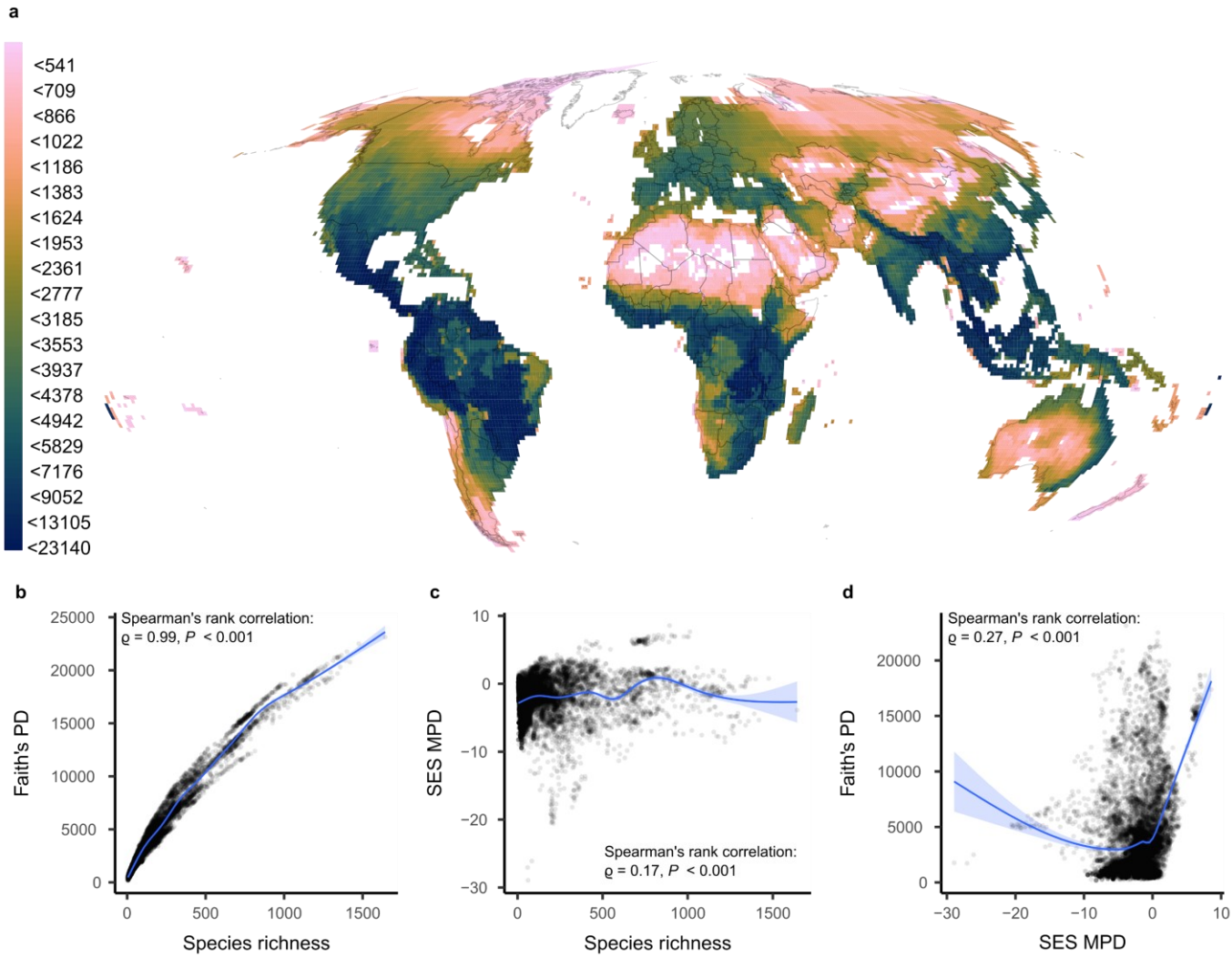
Realm	Group	SR	RR	PD
Afrotropic	Hotspots	43	12	58
Afrotropic	Non-hotspots	13	15	13
Australasia	Hotspots	11	6	19
Australasia	Non-hotspots	9	10	9
Indomalayan	Hotspots	25	10	23
Indomalayan	Non-hotspots	13	13	13
Nearctic	Hotspots	16	9	12
Nearctic	Non-hotspots	10	9	10
Neotropic	Hotspots	10	6	9
Neotropic	Non-hotspots	6	7	6
Palearctic	Hotspots	13	8	9
Palearctic	Non-hotspots	8	8	8



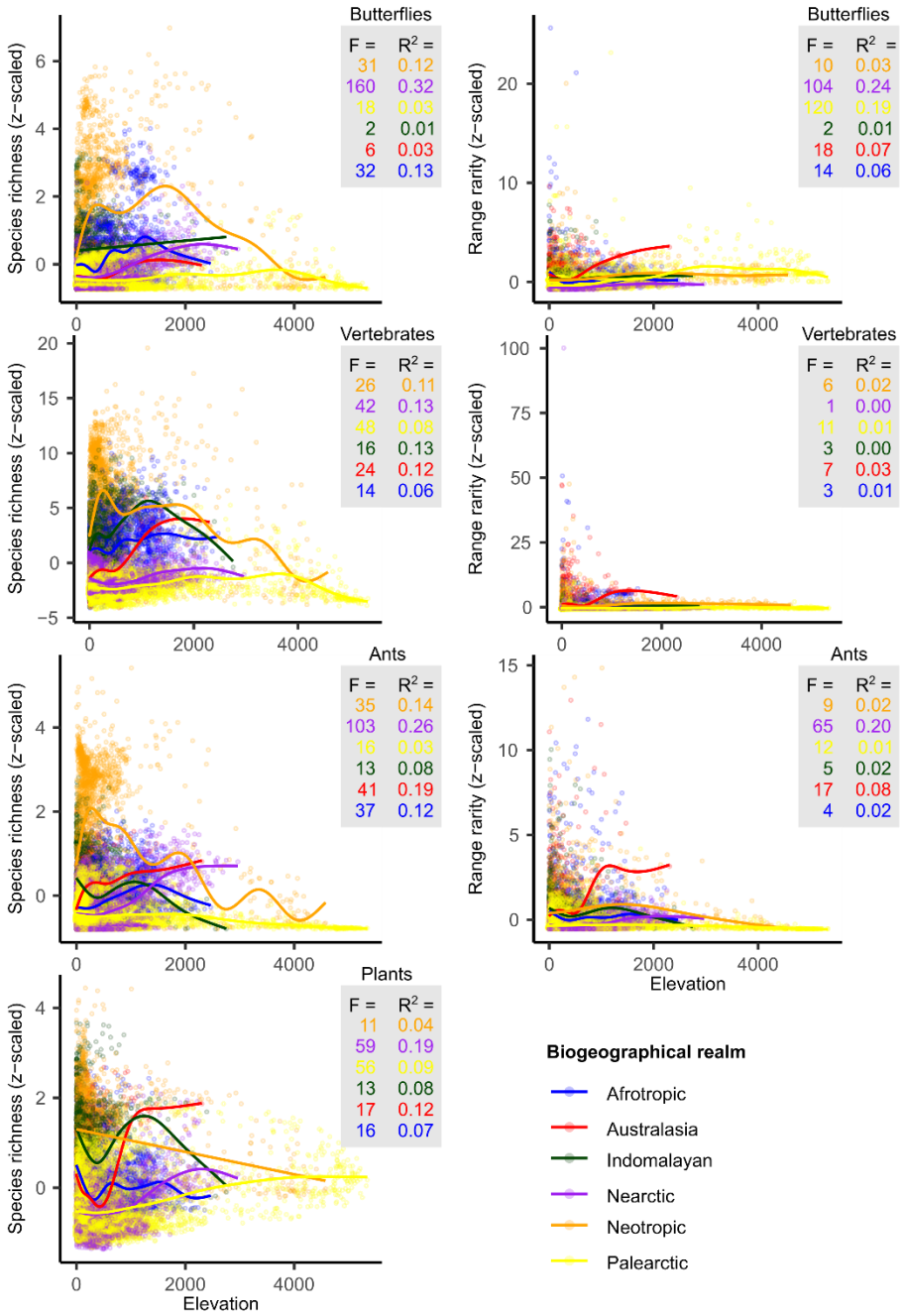
Supplementary Fig.1 | Data integration scheme. The core product is a composite of 6,650 species distribution models, expert range maps for additional 881 species and ecoregional range maps for additional 5,137 species. Orange arrows in the scheme are informative and blue are processing links. Ecoregional range maps are intersections of cleaned occurrence data and the terrestrial ecoregions of the world. SDMs use high-quality (cleaned) records and the binary predictions are masked by ecoregional ranges of species. If there were too few data or the quality of the species distribution model was not sufficient, expert range maps were used. If no expert range map was available or the available map did not cover all checklist countries, ecoregional ranges were used.



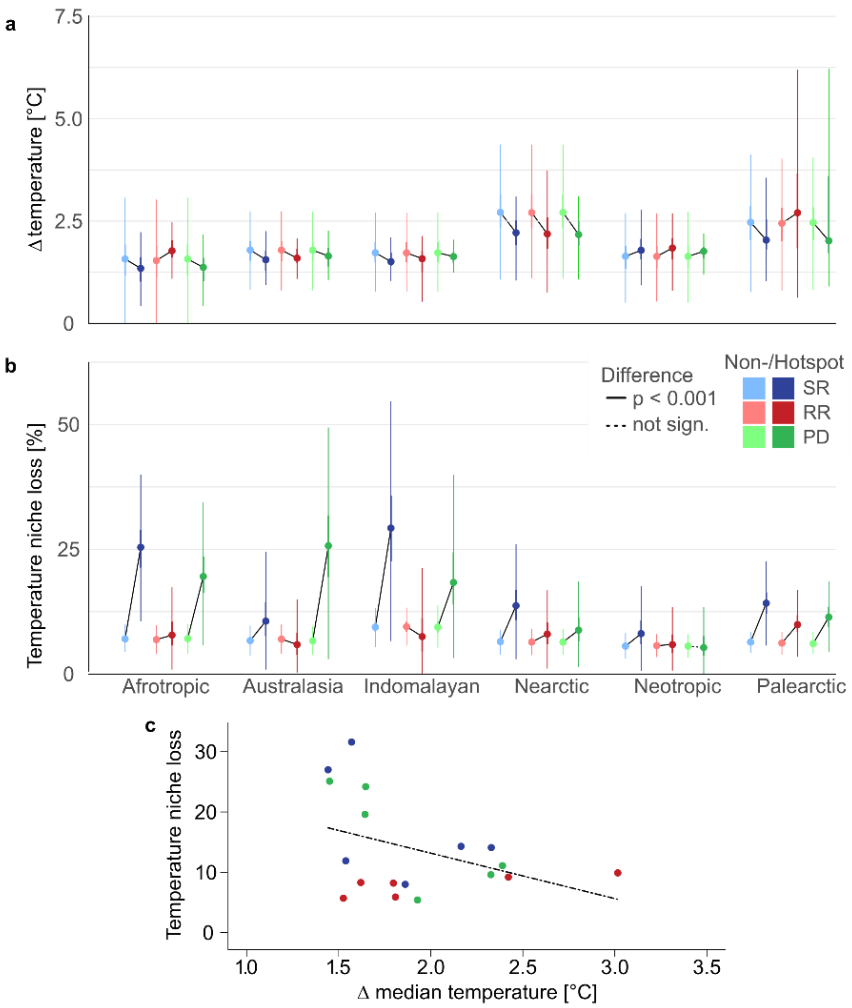
Supplementary Fig.2 | Data availability of different types of distributional data. Maps show the proportion of butterfly species for with species distribution models (6,650 species) (**a**), expert range maps (additional 881 species) (**b**), or ecoregional range maps (additional 5,137 species) (**c**) were used.



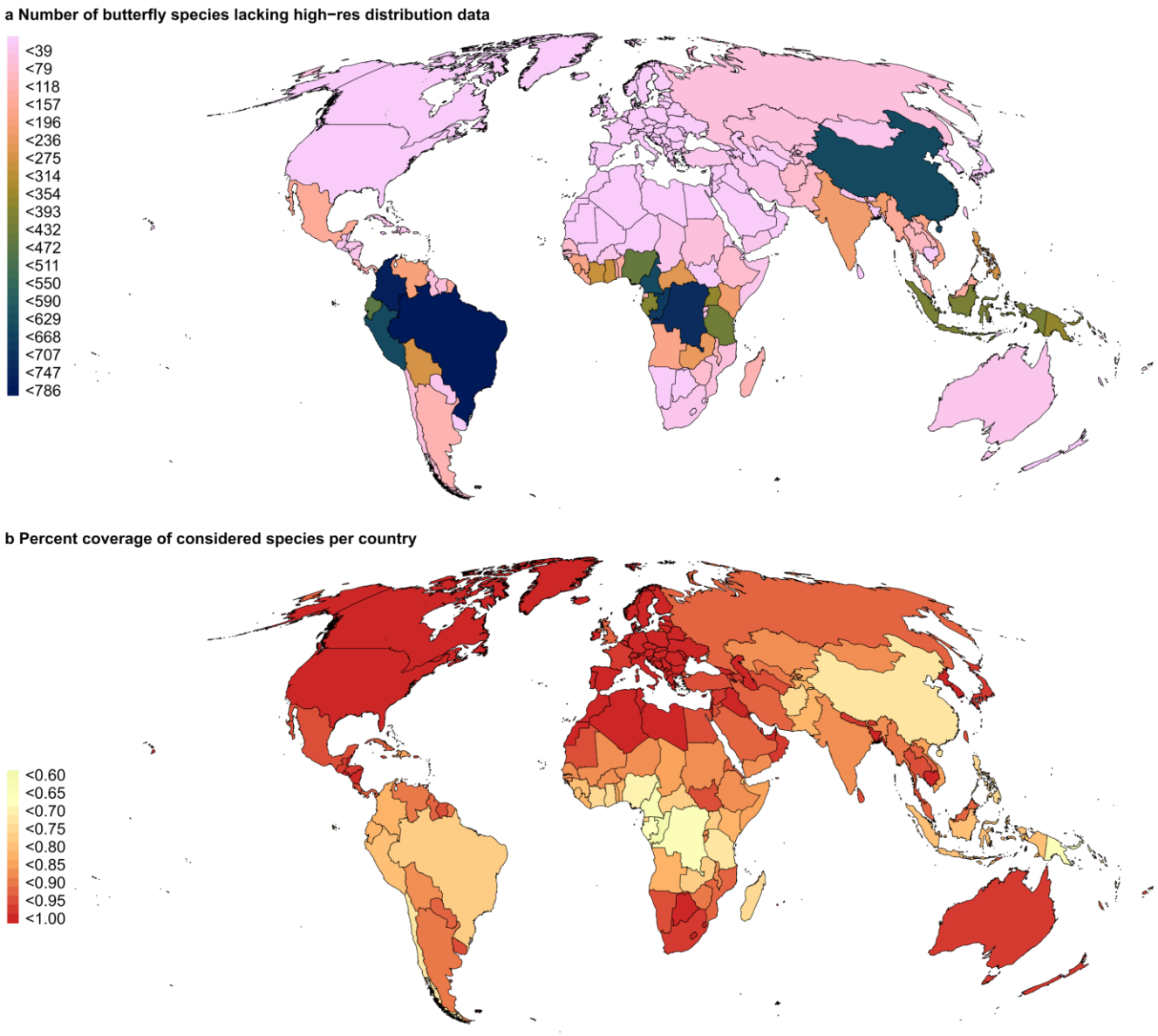
Supplementary Fig.3 | Global pattern of phylogenetic diversity (Faith's PD). a, Phylogenetic diversity calculated as the sum of branch lengths of the minimal spanning tree butterfly species co-occurring in a grid (110 km ×110 km). In all main analysis an alternative measure of PD (standardized effect sizes of mean pairwise distances; SES MPD) was used because of the strong dependence of Faith's PD is technically strongly correlated to species richness. Inset scatterplots show spline-based smoothed regressions with 95% confidence intervals (SE of fitted values; shaded areas) of the relationships between species richness and Faith's PD (**b**), species richness and SES MPD (**c**), and between SES MPD and Faith's PD (**d**) (*n* = 12,515 grid cells). All tests were two-sided.



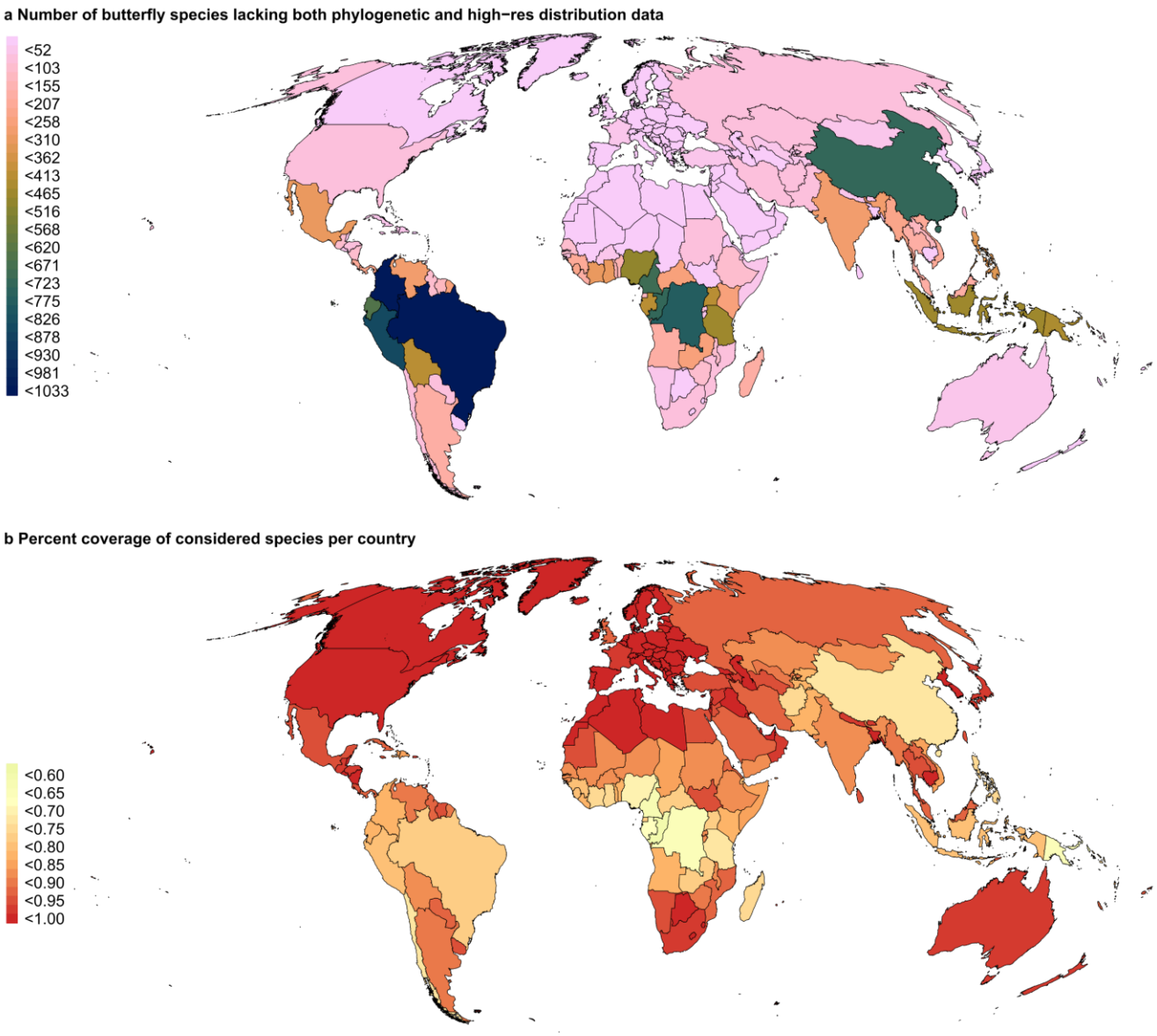
Supplementary Fig.4 | Relationships of species richness and range rarity with elevation for realms and taxa. Spline-based smoothed regressions with 95% confidence intervals (SE of fitted values; shaded areas) of standardized (z-scaled) species richness and range rarity of butterfly, vertebrate, ant, and plant assemblages against elevation for six biogeographical realms. F-values and explained variance (R^2) of these regressions are shown in inset boxes. Values for vertebrates were individually standardized and subsequently summed up for each assemblage. Sample sizes (*n*, i.e. grid cells) are: butterflies and vertebrates = 12,515; ants = 12,503; plants = 11,887.



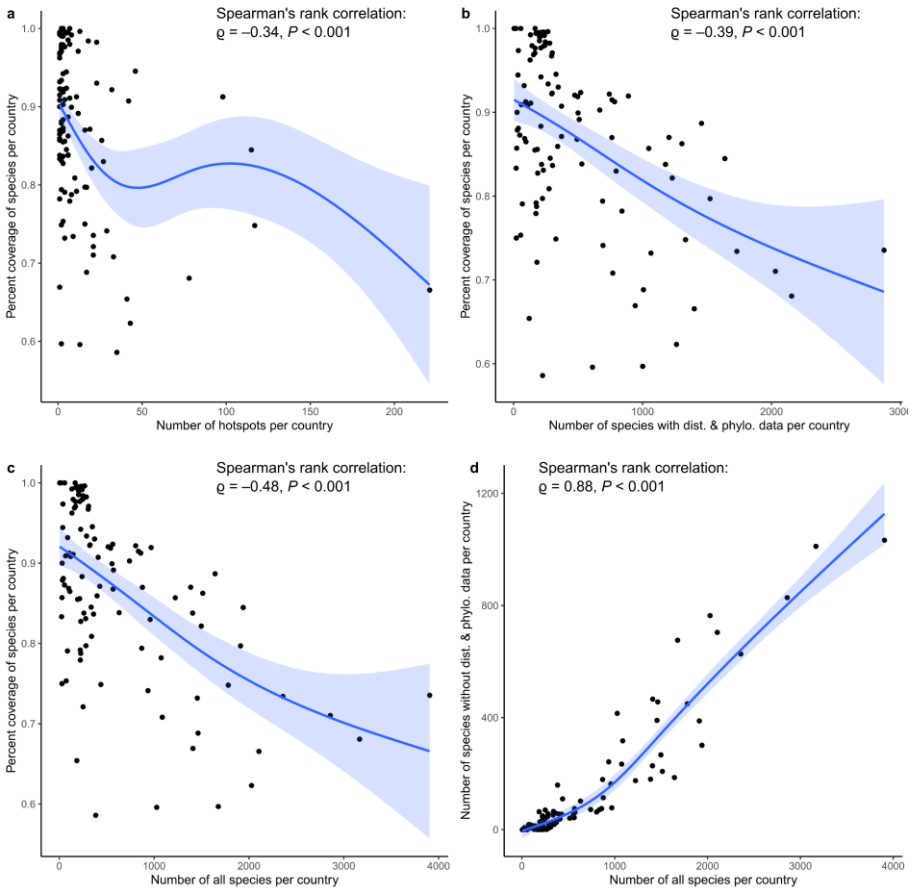
Supplementary Fig.5 | Projected future temperature niche loss and temperature difference in non-hotspots and hotspots. a, Temperature difference and **b**, temperature niche loss for non-hotspots and hotspots across realms and aspects of butterfly diversity under global warming (RCP 8.5). **c**, Relationship of temperature niche loss and temperature difference until the year 2070 among realm-level hotspots of species richness, range rarity, and phylogenetic diversity (ordered left to right) under an ensemble model for the scenario RCP 4.5. Plots in (**a**) and (**b**) show median values and the inner interquartile range of values and its 1.5-fold (dots, thick/thin bars). Sample sizes for calculating temperature differences (**a**), are (*n*; hotspots 5%/ non-hotspots 95%): Afrotropic = 1,901; Australasia = 1,182; Indomalayan = 977; Nearctic = 2,023; Neotropic = 1,873; Palearctic = 4,559. Estimates in (**b**) are derived from 1000 samples (*n*) for each combination of hotspot/non-hotspot areas and biogeographical realm. All test in (**a**, **b**) are two-sided and not adjusted for multiple comparisons. Notably, projected future temperature niche loss and temperature difference appear unrelated (two-sided test, Spearman's ρ = –0.43; P = 0.072; *n* = 18). Further analyses comparing temperature niche loss and temperature difference between non-hotspots and hotspots can be found in Extended Data Fig. 1 and 3.



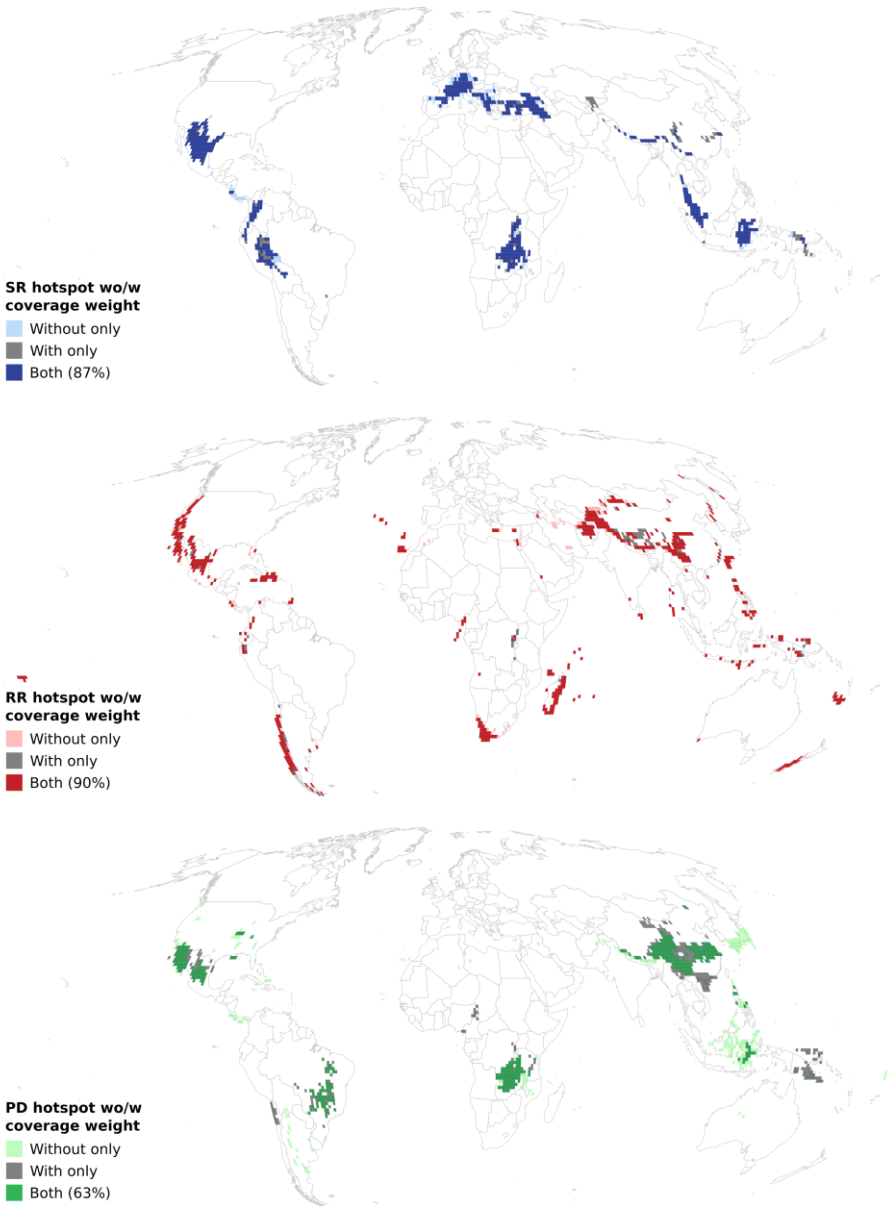
Supplementary Fig.6 | National coverage of distribution data. a, Absolute count of species without high resolution distribution data (SDMs, expert range maps or ecoregional range maps), **b**, Species count relative to the total of formally described species in a country (proportion; 19,317 species total; 13 species were lacking country-level distribution information). Color class intervals are scaled to equally wide classes for (**a**) and to equal frequency classes for (**b**). The maps are shown in a Mollweide equal-area projection. The proportion of included species was negatively associated with the number of accepted species per country (two-sided test, Spearman's rank correlation: $\rho = -0.59$, $n = 248$ countries, $P < 0.001$).



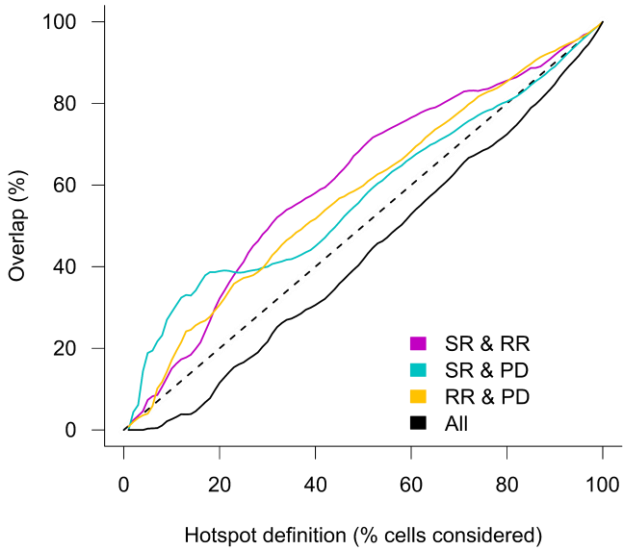
Supplementary Fig.7 | National coverage of combined phylogenetic and distribution data. a, Absolute count of excluded species, **b**, Species count relative to the total of formally described species in a country (proportion; 19,317 species total; 13 species were lacking country-level distribution information). Color class intervals are scaled to equally wide classes for (**a**) and to equal frequency classes for (**b**). Maps are shown in a Mollweide equal-area projection. The proportion of included species was negatively associated with the number of accepted species per country (two-sided test, Spearman's rank correlation: $\rho = -0.53$, $n = 248$ countries, $P < 0.001$).



Supplementary Fig.8 | Data coverage. Relationships of the percentage of species with phylogenetic and distribution data relative to total number of accepted butterfly species with the number of identified hotspots (any: SR, rarity, or PD) (**a**), the number of species with both phylogenetic and distribution data (**b**) and the number of accepted species per country (**c**). **d**, Relationship of the number of species without phylogenetic or distribution data and the number of all accepted species per country (n = 128 countries with at least one hotspot). Spline-based smoothed regressions with 95% confidence intervals (SE of fitted values; shaded areas) are only provided for visualizing trends. Statistics in the inset of each figure provide results from Spearman's rank correlations of the relationships. If the availability of data would have biased the hotspot identification, more hotspots should be found in countries with greater coverage. Our results show the opposite (**a**) and suggest this results from lesser covered countries having a greater number of species (**b, c**). Their top-ranked position does not change even when adding hundreds of currently missing species (**d**, i.e. the number of included species is monotonically positively related to the number of all accepted species). For maps of the species coverage per country refer to Supplementary Fig. 6. All tests were two-sided.



Supplementary Fig.9 | Robustness of hotspot locations against missing data. Hotspots (top 5%) of butterfly species richness, range rarity, and phylogenetic diversity across realms, with adjustments made for the diversity value of cells based on country-specific species coverage (see Supplementary Fig. 2, 3) as inverse weight. Hotspots robust to weighting are depicted in full colors, while hotspots identified only prior to weighting are shown as light-colored cells. Hotspots newly identified following the coverage-weighting are shown as dark gray grid cells.



Supplementary Fig.10 | Robustness of congruence among diversity aspects to an expanded hotspot definition. Overlap of among hotspots of species richness, range rarity and phylogenetic diversity (SR, RR, PD) across varying hotspot definitions, ranging from 1% to 100% of the total number of cells (max *n* = 12,515 grid cells), in 1% increments.