Title: Global assessment of current extinction risks and future challenges for turtles and tortoises

Supplementary Table 1. The proportion of threatened species among the 14 families and 8 major biogeographical realms (including Marine and unclassifiable). We employed binomial distribution tests to assess whether chelonian families exhibited threatened species proportions deviating from random expectation. Using Red List extinction risk data, 335 species (categorized as non-threatened: LC, NT; threatened: VU, EN, CR, EX) were analyzed. The null hypothesis assumed uniform threat distribution across families (expected threatened proportion = 196/335 = 0.585). For each family, we tested if the observed number of threatened species (K) in a family with N species followed the binomial probability framework. To control for Type I error in multiple independent tests, the Dunn-Sidak method was used to adjust critical values. For 14 families independent tests, the adjusted critical values corresponding to significance levels of 5% and 1% are $p < 3.66 \times 10^{-3}$ and $p < 7.18 \times 10^{-4}$, respectively. For independent tests of 8 major biogeographical realms, the adjusted critical values corresponding to significance levels of 5% and 1% are $p < 6.39 \times 10^{-3}$ and $p < 1.25 \times 10^{-3}$, respectively.

	All species	Threatened species	Probability of threatened	P value of the binomial test	adjusted critical value at 0.05	adjusted critical value at 0.01
Carettochelyidae	1	1	1	0.585	0	0
Chelidae	51	14	0.275	0.00000522	1	1

Cheloniidae	5	4	0.8	0.243	0	0
Chelydridae	5	3	0.6	0.345	0	0
Dermatemydidae	1	1	1	0.585	0	0
Dermochelyidae	1	1	1	0.585	0	0
Emydidae	52	26	0.5	0.0513	0	0
Geoemydidae	69	50	0.725	0.00585	0	0
Kinosternidae	30	4	0.133	0.000000375	1	1
Pelomedusidae	16	2	0.125	0.000184	1	1
Platysternidae	1	1	1	0.585	0	0
Podocnemididae	8	8	1	0.0137	0	0
Testudinidae	65	56	0.862	0.00000107	1	1
Trionychidae	30	25	0.833	0.00265	1	0

	All species	Threatened species	Probability of threatened	P value of the binomial test	adjusted critical value at 0.05	adjusted critical value at 0.01
Afrotropics	52	32	0.615	0.102	0	0
Australasia	35	14	0.4	0.0121	0	0
Indomalaya	73	62	0.849	0.000000824	1	1
Marine	6	5	0.833	0.171	0	0
Nearctic	65	27	0.415	0.00228	1	0
Neotropics	80	40	0.5	0.0275	0	0
Palearctic	15	10	0.667	0.174	0	0
unclassifiable	9	6	0.667	0.241	0	0

Supplementary Table 2. The rates of trait evolution compared to mean temperature change (Climate), extreme drought (SPEI), heatwave (WSDI), human population expansion (Human), and forest degradation (Forest).

Variable	Activity time	Diet	Maximum lifespan	Maximum Body length	Mean clutch size
Rate of trait evolution	2.39E-06	4.01E-06	7.48E-06	5.84E-06	4.61E-06

	Climate_ssp126	Climate_ssp585	SPEI126	SPEI585	WSDI126	WSDI585	Human_ssp1	Human_ssp5	Forest_ssp1	Forest_ssp5
Mean	0.003781	0.040721	0.032621	0.305602	2.185857	3.827788	0.173282	0.249297	0.026254	0.667297
Mean-SE	0.003496	0.038203	0.027729	0.143174	2.149019	3.784867	0.157997	0.232629	0.02181	0.252497
Mean+SE	0.004065	0.04324	0.037514	0.468031	2.222695	3.870709	0.188568	0.265964	0.030698	1.082097

Supplementary Table 3. The model-averaged estimates were derived using the IUCN or TFTSG Red List assessments as the response variable. We employed Phylogenetic Generalized Least Squares to examine the influence of eight key factors in determining the extinction risk of species across ordinal risk categories (0-5, ranging from Least Concern (LC) to Extinct (EX)). Significant variables ($p < 0.05$, two-sided, marked in grey) within the 95% confidence set are presented along with model-averaged estimates and adjusted unconditional standard errors (SE).

IUCN Red list	Estimate	SE	Z	p
(Intercept)	1.993909	1.089601	1.8299	0.06843
Year of description	-0.057716	0.100353	-0.5751	0.56571
Maximum body length	0.147042	0.103934	1.4148	0.15837
Endemicity	-0.439979	0.291731	-1.5082	0.13276
Range size	-0.622011	0.119085	-5.2233	3.67E-07
Extreme droughts	-0.097469	0.098615	-0.9884	0.32391
Functional distinctness	0.222155	0.086195	2.5774	0.01052
Mean annual temperature	0.136699	0.103793	1.317	0.18902

No. of threats	0.234368	0.05662	4.1393	4.75E-05

TSTSG Red List	Estimate	SE	*Z*	*p*
(Intercept)	1.886984	1.278788	1.4756	0.141015
Year of description	0.046987	0.07898	0.5949	0.552307
Maximum body length	0.206302	0.09126	2.2606	0.024443
Endemicity	-0.464077	0.246243	-1.8846	0.060369
Range size	-0.658813	0.100663	-6.5447	2.31E-10
Activity time	-0.103155	0.062756	-1.6438	0.101191
Extreme droughts	-0.052725	0.074667	-0.7061	0.480612
Functional distinctness	0.200788	0.075019	2.6765	0.007816
No. of threats	0.269905	0.042626	6.3319	8.02E-10

Supplementary Table 4. Hypotheses on the relationships between predictor factors and extinction risk.

Predictor factor	Treatment of factor	Prediction	Hypothesis	References
Activity time	nocturnal (0), crepuscular (1), diurnal (2), and cathemeral (3, day and night)	+	nocturnal and cathemeral species have activity patterns that highly coincide with human activities	1, 2, 3
Body mass	Continuous: maximum body mass (g)	+/−	Large species often have small population densities and slow life histories. Alternatively, small species are more susceptible to competition and predation by exotic species.	1, 2, 4
Diet	Categorical: omnivores (0), herbivores (1), and carnivores (2)	+	Carnivores are often less abundant and hardly to restore in their population following harvesting.	1, 2, 4
Insular endemism	Categorical: island (1) and	+	Island endemic species have small range sizes and are	2, 4

	mainland (0)		vulnerable to extrinsic threats	
Maximum life span	Continuous: Data from references 5, 6, 7	+	Species with longer life spans may have much slower life histories and are highly vulnerable to human collection.	8
Clutch size	Continuous: Data from references 5, 6, 7	−	Species with smaller clutch sizes are likely to be prone to extinction due to a weak recovery potential from small population sizes	9, 10
Geographical range size	Continuous: Extent of Occurrence (km^2) of lizards from the GARD 1.7	−	Small-ranged species may have an elevated extinction risk due to demographic and environmental stochasticity, and inbreeding probability	1, 2, 4
Functional distinctness	Continuous: Average functional distance from a species to all other chelonians	+	Species with high rarity in the wild are more likely to be threatened by human collection.	5

Evolutionary distinctness	Continuous: the evolutionary isolation of each species	+	Species with high rarity in the wild are more likely to be threatened by human collection.	5
Year of description	Continuous: From IUCN Red List	−	Species described earlier may have a broader distribution, potentially leading to a reduced risk of extinction.	11
Annual temperature	Continuous: WorldClim 2	−	Reptiles are ectotherms with slower life histories in cooler regions.	2, 4
Temperature seasonality	Continuous: WorldClim 2	+/−	Areas experiencing strong seasonal temperatures have less stable environments and potentially higher human disturbance. Alternatively, species that are adapted to stable climates may have smaller ranges and are less resilient than species in seasonal environments	12, 13
Annual	Continuous: WorldClim 2	+	Rainy and productive regions may also have higher	2, 4

precipitation			human disturbance	
Precipitation seasonality	Continuous: WorldClim 2	+/−	Areas experiencing strong seasonal precipitation may have enhanced predation and habitat alternation, while less seasonal precipitation often refers to a more constrained distribution of species	12, 13
Extreme drought	Continuous: Standardized Precipitation Evapotranspiration Index (SPEI)	−	Droughts have been linked to declines in survival rates, habitat loss, and changes in predation pressure for turtles.	14, 15
Heatwave	Continuous: Warm Spell Duration Index (WSDI)	+	Heatwaves could conceivably affect temperature-dependent sex determination and alter their existing habitat	16, 17
Human threat index	Continuous: summing the	+	Reptiles exposed to higher human disturbance and	2, 3, 4

	number of threats documented for a focal species	impact often have an increased extinction risk

References:

1 Purvis, A. et al. Predicting extinction risk in declining species. *Proc. Roy. Soc. London. Ser. B: Biol. Sci.* **267**, 1947–1952 (2000).

2 Senior, A. F. et al. Correlates of extinction risk in Australian squamate reptiles. *J. Biogeogr.* **48**, 2144-2152 (2021).

3 Zhong, Y. et al. Biological and extrinsic correlates of extinction risk in Chinese lizards. *Curr. Zool.* **68**, 285-293 (2022).

4 Böhm, M. et al. Correlates of extinction risk in squamate reptiles: the relative importance of biology, geography, threat and range size. *Glob. Ecol. Biogeogr.* **25**, 391-405 (2016).

5 Colston, T. J. et al. Phylogenetic and spatial distribution of evolutionary diversification, isolation, and threat in turtles and crocodilians (non-avian archosauromorphs). *BMC Evol. Biol*. **20**, 1-16 (2020).

6 Rodríguez-Caro, R. C. et al. Anthropogenic impacts on threatened species erode functional diversity in chelonians and crocodilians. *Nat. Commun.* **14**, 1542 (2023).

7 Oskyrko, O. et al. ReptTraits: a comprehensive dataset of ecological traits in reptiles. *Sci. Data*. **11**, 243 (2024).

8 Bu, R. et al. The evolutionary advantages of chelonians are making them vulnerable to extinction in the Anthropocene. *Integrative Conservation*,

2, 109-111 (2023).

9 Hero, J. M. et al. Ecological traits of declining amphibians in upland areas of eastern Australia. *J. Zool.* **267**, 221-232 (2005).

10 Murray, B. R. et al. Life-history and ecological correlates of decline and extinction in the endemic Australian frog fauna. *Austral Ecol.* **30**, 564-571 (2005).

11 Liu, J. et al. Undescribed species have higher extinction risk than known species. *Conserv. Lett.* **15**, e12876 (2022).

12 Sodhi, N. S. et al. Measuring the meltdown: drivers of global amphibian extinction and decline. *PloS One*, **3**, e1636 (2008).

13 Tingley, R. et al. Life-history traits and extrinsic threats determine extinction risk in New Zealand lizards. *Biol. Conserv*. **165**, 62-68 (2013).

14 Chessman, B. C. Declines of freshwater turtles associated with climatic drying in Australia’ s Murray-Darling Basin. *Wildl. Res.* 38, 664–671 (2011).

15 Lovich, J. E. et al. Climatic variation and tortoise survival: Has a desert species met its match? *Biol. Conserv*. **169**, 214–224 (2014).

16 Gu, S. et al. Meta-analysis reveals less sensitivity of non-native animals than natives to extreme weather worldwide. *Nat. Ecol. Evol*. **7**, 2004–2027 (2023).

17 Murali, G. et al. Future temperature extremes threaten land vertebrates. *Nature*, **615**, 461-467 (2023).

Supplementary Table 5. Threat classification based on the IUCN threat classification scheme.

Category	IUCN threat classification scheme
Habitat destruction	1. Residential and commercial development
Habitat destruction	2. Agriculture and Aquaculture
Habitat destruction	3. Energy production and mining
Habitat destruction	4. Transportation and service corridors
Overexploitation	5.1 Hunting and collecting terrestrial animals
Habitat destruction	5.2 Gathering terrestrial plants
Habitat destruction	5.3 Logging and wood harvesting
Overexploitation	5.4 Fishing and harvesting aquatic resource
Habitat destruction	6. Human intrusion and disturbance
Habitat destruction	7. Natural system modifications
Invasive species	8. Invasive and other problematic species, genes and diseases
Pollution	9. Pollution

Supplementary Table 6. The model-averaged estimates were derived from Phylogenetic Generalized model with the Ornstein–Uhlenbeck process for all species. Significant variables ($p < 0.05$, two-sided, marked in grey) within the 95% confidence set are presented along with model-averaged estimates and adjusted unconditional standard errors (SE).

	Estimate	SE	Z	p
(Intercept)	0.41825	0.07782	5.375	1.00E-07
Mean annual temperature	0.0444	0.0294	1.51	0.13102
Functional distinctness	0.076	0.02512	3.025	0.00249
Range size	-0.14971	0.02924	5.119	1.65E-05
Number of threats	0.09522	0.01453	6.553	3.20E-04
Maximum body length	0.04641	0.03055	1.519	0.12877
Year of description	0.03202	0.02689	1.191	0.23368
Maximum lifespan	0.02247	0.0232	0.968	0.33281
Activity time	-0.02323	0.0229	1.014	0.31044

Heatwaves	-0.01026	0.02881	0.356	0.72176
Extreme droughts	-0.01703	0.02499	0.682	0.49546
Endemicity	-0.05443	0.08663	0.628	0.52978

Supplementary Table S7. All models exhibit a variance inflation factor (VIF) for each variable of less than 5. Abbreviations: AT, Activity time; EN, Endemicity; ML, Maximum lifespan; BL, Body length; CS, Clutch size; RS, Geographic range size; FD, Functional distinctness; ED, Evolutionary distinctness; MAT, Mean annual temperature; MAP, Mean annual precipitation; NT, No. of Human threats.

All species	*YD*	*BL*	*EN*	*RS*	*AT*	*SPEI*	*FD*	*NT*
VIF	1.503057	1.438691	1.897015	2.225155	1.127198	1.103862	1.309624	1.084627

Aquatic	*YD*	*BL*	*RS*	*AT*	*SPEI*	*FD*	*MAT*	*NT*
VIF	1.958672	1.576856	2.160882	1.144578	1.249342	1.362648	1.419551	1.264309

Terrestrial	*EN*	*RS*	*AT*	*FD*	*NT*
VIF	4.103665	4.181518	1.066725	1.525349	1.058503

Afrotropics	*BL*	*EN*	*RS*	*MAP*	*NT*
VIF	1.589704	3.676527	3.038514	1.75479	1.2534

Australasia	*YD*	*RS*	*FD*	*ED*	*SPEI*	*WSDI*	*MAT*	*NT*
VIF	1.639442	2.821345	1.511816	1.438576	2.280559	2.510076	1.960038	2.516567

Indomalaya	*BL*	*AT*	*RS*	*MAT*	*NT*
VIF	1.17083	1.072559	1.097253	1.22275	1.287442

Nearctic	*YD*	*FD*	*RS*	*NT*
VIF	2.676332	1.011116	2.661	1.020904

Neotropics	*YD*	*BL*	*RS*	*LS*	*CS*	*FD*	*SPEI*	*NT*

VIF	2.010263	2.680453	3.447558	2.406952	2.070917	1.335273	1.975729	1.347895