Supplementary Information – Pyron et al. Tetrapod Extinction

Supplementary Methods

Moura et al. (2024) introduced TetrapodTraits[1], a phylogeny-informed resource containing 75 fully sampled variables representing 24 attributes for all 33,281 species considered here, including traits such as, body size, activity time, micro- and macrohabitat, biogeography, insularity, ecosystem, environmental preferences, human influence, and threat status. We augmented this database with additional 11 attributes related to species developmental mode, life history, diet, major threats, population trends, and biome prevalence, all compiled from original sources (e.g., articles, books, grey literature, and websites) and previously available databases[2–14]. All sources are recorded in the updated database (see Data Availability Statement) – our new search included 1,504 sources, and we here highlight references contributing >100 records.

To improve data coverage (Supplementary Table 1), we searched Google Scholar and Web of Science for genera and families missing life history and diet data, improving the representation of major tetrapod clades. Search terms in English (e.g., lifespan, longevity, age, clutch size, litter size, diet), Portuguese (e.g., tempo de vida, longevidade, idade, tamanho da ninhada, dieta), and Spanish (e.g., esperanza de vida, longevidad, edad, tamaño de la nidada, dieta) were combined with scientific names of targeted species. To maximize data usage, we applied IUCN synonyms to update species taxonomy in external data sources and flagged each data entry to prevent duplicates. Only unique synonyms – scientific names associated with a single valid species – were considered for taxonomic matches. Our species-level attribute dataset contained 30 predictors and 5 summed factors with strongly hypothesized relationships to conservation status that were ~100% complete for four of the variables, and 91% complete overall.

Data on maximum longevity (in years) were available for 7,619 species (22.9%), representing at least one species in 85.9% of families and 49.2% of genera. Average litter or clutch size was retrieved for 18,638 species (56%), covering 96.3% of families and 86.3% of genera. Litter or clutch size was typically represented by the midpoint between reported maximum and minimum values or the geometric mean across available samples, although other measures of central tendency or single reported values were also included to maximize data coverage. Our longevity and litter or clutch size data was derived from 597 sources[2–5,7–12].

We retrieved diet data for 23,594 species (70.9%), encompassing at least one representative in 99.8% of families and 96.4% of genera. Diet categories were not mutually exclusive and followed those in the EltonTraits database[14], allowing species diet to include multiple food sources, namely: invertebrates, vertebrate ectotherms, vertebrate endotherms, fishes, unknown vertebrates, scavengers, fruits, nectar, seeds, and other plant materials. For birds and mammals, we adapted EltonTraits to indicate presence-absence data for diet categories when at least 20% of a species' relative usage was attributed to a given category. To ensure consistency across clades, we applied the same 10 diet categories to reclassify the diet data compiled for amphibians and reptiles. We also recorded the total number of diet categories for each species as diet breadth. We consulted 913 sources, including articles, books, grey literature, websites, and databases[6,7,9,13–17].

Information on developmental mode was represented by three key traits: direct development, larval stage, and viviparity. Given the deep homology of these traits across lineages, we applied taxonomic imputation for missing data, leveraging phylogenetic conservatism in developmental traits (e.g., most amphibians exhibit larval stage, while birds are oviparous). This approach allowed us to impute values for larval stage and direct development for 15,904 species (all mammals and birds) and viviparity for 9,994 species (all birds and one bat). Overall, this information was available for 31,583 species (94.9%), covering all families and 98.8% of genera. We included data on developmental mode derived from 27 sources[7,9,10,18].

While non-Data Deficient (non-DD) threat statuses were available for 29,803 tetrapod species (see Moura et al., 2024), this does not imply the availability of threat type or population trend data, as threat status assessments can be based solely on geographic range size without further information on threats or trends (see https://www.iucnredlist.org/). Using the *rredlist* package[19], we extracted threat type data for 16,876 species (50.7%) and population trend for 22,741 species (68.3%). Threat type variables corresponded to the first level of the IUCN Threats Classification Scheme v. 3.3, comprising 12 binary variables identifying whether species declines are associated with drivers such as food production, habitat destruction, human disturbance, overexploitation, invasive species, pollution, climate change, and others. An additional variable captured the total number of threat types recorded for each species. Finally, population trend was represented as an ordinal variable with three numeric levels: decreasing (0), stable (1), or increasing (2). Data on biome prevalence was represented by 14 interval-scaled attributes indicating the proportion of the previously published species' range maps[1] overlapped by each WWF biome (BiomeNum_1 to BiomeNum_14)[20].

Anomalous behavior in exploratory model testing led us to make a small number of ad-hoc changes for attributes that were not recorded in the original data sources for some species. For *Homo sapiens,* population trend was set to 2 (increasing), and for both *H. sapiens* and *Equus caballus* (domestic horses)*,* total number of threats was set to 0. Finally, we refer to an un-named species of West African *Osteolaemus* as *Osteolaemus "afzelli"* based on an existing name with apparent priority for this lineage[21], given a need for complete binomials in our code pipeline. This is not a formal taxonomic recommendation, and is hereby disclaimed as a nomenclatural act under Article 8.3 of the International Code of Zoological Nomenclature[22].

The major factor loadings for present-day (PC1/2), extinction-weighted (pEX; PC1/2x), and survival-weighted (1 - pEX; PC1/2f) are given in Supplementary Table 8. The non-phylogenetic factors are illustrated in Fig. 3c and Extended Data Fig. 9a, b – the phylogenetic PC1 primarily separates amphibians from other tetrapods (Extended Data Fig. 10a). The shifts between the factor loadings of PC1/2x and PC1/2f (calculated as the Euclidean distance) are illustrated in Fig. 3f and Extended Data Fig. 9e. When loadings were redundant (e.g., BiomeNum_1/AnnuPrecip) or complimentary (e.g., DirectDev/Larval Stage), only the first factor was illustrated. For Shifts between extinction- and survival-weighted attribute space, we did not illustrate factors inducing structure between clades without variability within clades (e.g., DirectDev/LarvalStage).

Supplementary Tables

Supplementary Table 1 | Name, type, and species-level coverage (%) for 35 attributes and 98 total variables. Those marked "(log)" were ln-transformed for analysis but presented in their original units in the TetrapodTraits Zenodo repository 10.5281/zenodo.10530617[1].

Name	Type	Coverage
1. Body length (mm)	One continuous variable (log)	100%
2. Body mass (g)	One continuous variable (log)	100%
3. Activity time	Two binary variables	100%
4. Microhabitat	Five binary variables	100%
5. Macrohabitat	Seventeen binary variables	97.0%
6. Macrohabitat breadth	One continuous variable (integer)	97.0%
7. Ecosystem	Three binary variables	98.2%
8. Ecosystem breadth	One continuous variable (integer)	98.2%
9. Geographic range size	One continuous variable (log)	99.9%
10. Latitude	One continuous variable	99.9%
11. Longitude	One continuous variable	99.9%
12. Realm occupancy	Eight continuous variables range [0-1]	99.9%
13. Insularity	One binary variable	99.9%
14. Annual Mean Temperature	One continuous variable (log)	99.9%
15. Annual Precipitation	One continuous variable (log)	99.9%
16. Temperature Seasonality	One continuous variable (log)	99.9%
17. Precipitation Seasonality	One continuous variable (log)	99.9%
18. Elevation	One continuous variable (log)	99.9%
19. ETA50K	One continuous variable (log)	99.9%
20. Human Density	One continuous variable (log)	99.9%
21. Prop. of Urban Area	One continuous variable range [0-1]	99.9%
22. Prop. of Cropland Area	One continuous variable range [0-1]	99.9%
23. Prop. of Pasture Area	One continuous variable range [0-1]	99.9%
24. Prop. of Rangeland Area	One continuous variable range [0-1]	99.9%
25. Max longevity (years)	One continuous variable (log)	22.9%
26. Avg. brood size	One continuous variable (log)	56.0%
27. BiomeCoverage	14 continuous variables range [0-1]	99.9%
28. Diet	10 binary variables	70.9%
29. Diet breadth	One continuous variable (integer)	70.9%
30. Direct development	One binary variable	94.9%
31. Larval stage	One binary variable	94.9%
32. Viviparity	One binary variable	94.9%
33. Threat type	12 binary variables	50.7%
34. Total number of threats	One continuous variable (integer)	50.7%
35. Population Trend	One ordinal variable	68.3%

Supplementary Table 2 | Parameter estimates for the best-fit model_196 for pEX as a function of Clade, ED, and DR (dAIC = 102), showing estimates, error and credible intervals, and ESS, fit in 'brms' with the Beta() family, logit/log links for μ/ϕ, formulae of μ ~ ED * DR * Clade | ϕ ~ ED * DR * Clade, and 5,000 iterations from 4 chains.

Coefficients	Est.	Err.	LCI	UCI	Bulk	Tail
(Intercept)	0.89	0.24	0.42	1.35	2619	4486
phi_(Intercept)	-0.92	0.34	-1.58	-0.25	2614	4405
ED	-0.85	0.14	-1.12	-0.57	3538	5630
DR	0.21	0.11	0	0.42	4798	5444
CladeAves	-3.01	0.24	-3.48	-2.52	2663	4723
CladeCrocodylia	0.14	0.94	-1.72	1.98	13070	7472
CladeLepidosauria	-2.67	0.26	-3.18	-2.17	2798	4754
CladeMammalia	-1.6	0.25	-2.1	-1.11	2809	4742
CladeTestudines	-0.86	0.5	-1.85	0.12	6368	7140
ED:DR	-0.11	0.03	-0.17	-0.06	2627	4322
ED:CladeAves	1.18	0.16	0.86	1.5	4049	5880
ED:CladeCrocodylia	-0.11	0.51	-1.1	0.89	11971	7017
ED:CladeLepidosauria	1.39	0.18	1.05	1.73	4311	6655
ED:CladeMammalia	0.23	0.18	-0.12	0.58	4401	6525
ED:CladeTestudines	0.38	0.35	-0.29	1.06	7965	6903
DR:CladeAves	0.27	0.12	0.02	0.51	5290	6693
DR:CladeCrocodylia	-0.61	0.76	-2.07	0.88	10918	6672
DR:CladeLepidosauria	0.39	0.14	0.11	0.67	6078	7150
DR:CladeMammalia	-0.14	0.13	-0.39	0.12	5810	7150
DR:CladeTestudines	-0.35	0.25	-0.85	0.15	8869	7141
ED:DR:CladeAves	0.07	0.03	0.01	0.13	2917	4687
ED:DR:CladeCrocodylia	0.11	0.15	-0.18	0.39	11382	7676
ED:DR:CladeLepidosauria	0.09	0.03	0.03	0.16	3140	5308
ED:DR:CladeMammalia	-0.02	0.04	-0.09	0.05	3640	5956
ED:DR:CladeTestudines	0.07	0.06	-0.04	0.18	6333	6600
phi_ED	1.15	0.2	0.75	1.55	3408	4872
phi_DR	-0.07	0.14	-0.35	0.21	4931	5914
phi_CladeAves	3.37	0.35	2.69	4.07	2656	4393
phi_CladeCrocodylia	30.17	17.77	-4.75	65.2	6388	6600
phi_CladeLepidosauria	2.85	0.37	2.12	3.58	2799	4525
phi_CladeMammalia	2.03	0.37	1.3	2.74	2710	4747
phi_CladeTestudines	2.57	0.98	0.61	4.45	6055	6778
phi_ED:DR	0.14	0.04	0.06	0.21	2594	4294
phi_ED:CladeAves	-1.61	0.23	-2.08	-1.15	3760	5502
phi_ED:CladeCrocodylia	-10.02	6.22	-22.59	1.89	6578	6685
phi_ED:CladeLepidosauria	-1.77	0.25	-2.26	-1.27	4092	6532
phi_ED:CladeMammalia	-0.74	0.25	-1.22	-0.26	4013	5322
phi_ED:CladeTestudines	-0.77	0.67	-2.06	0.53	7216	6757
phi_DR:CladeAves	-0.59	0.17	-0.92	-0.26	5803	6683
phi_DR:CladeCrocodylia	7.1	4.53	-2.09	15.72	7068	7078
phi_DR:CladeLepidosauria	-0.61	0.19	-0.99	-0.22	6552	7385
phi_DR:CladeMammalia	-0.06	0.17	-0.39	0.27	5533	6527
phi_DR:CladeTestudines	1.06	0.41	0.24	1.86	9953	7882
phi_ED:DR:CladeAves	-0.08	0.04	-0.17	0	2913	5104
phi_ED:DR:CladeCrocodylia	-2.41	1.4	-5.14	0.35	6357	6530
phi_ED:DR:CladeLepidosauria	-0.12	0.05	-0.22	-0.03	3184	4785
phi_ED:DR:CladeMammalia	-0.03	0.05	-0.13	0.08	3456	5581
phi_ED:DR:CladeTestudines	-0.32	0.11	-0.53	-0.1	6077	6683

Supplementary Table 3 | Parameter estimates for the best-fit models for pEX as a function of Clade, ED, and DR, showing estimates, error and intervals, and ESS by Clade, with the most-complex model ($\mu \sim ED * DR \mid \phi \sim ED * DR$) as the best fit for Amphibia, Aves, and Mammalia, and a slightly simpler model ($\mu \sim ED + DR \mid \phi \sim ED + DR$) for Lepidosauria.

Coefficients	Est.	Err.	LCI	UCI	Bulk	Tail
Amphibia_25						
Intercept	1.62	0.28	1.08	2.16	2474	2705
phi_Intercept	-1.27	0.33	-1.93	-0.61	2483	2741
ED	-1.23	0.16	-1.55	-0.92	2503	2205
DR	0.32	0.12	0.10	0.54	2615	2519
ED:DR	-0.19	0.03	-0.25	-0.13	2365	2476
phi_ED	1.32	0.20	0.93	1.71	2722	2853
phi_DR	-0.13	0.14	-0.41	0.15	3267	2838
phi_ED:DR	0.18	0.04	0.10	0.25	2427	2420
Aves_25						
Intercept	-2.14	0.06	-2.26	-2.02	2740	2875
phi_Intercept	2.47	0.09	2.28	2.65	2751	2625
ED	0.35	0.08	0.19	0.51	2120	2588
DR	0.48	0.06	0.36	0.60	2313	2381
ED:DR	-0.04	0.01	-0.07	-0.01	2695	2435
phi_ED	-0.47	0.12	-0.71	-0.23	2355	2396
phi_DR	-0.65	0.09	-0.84	-0.47	2372	2514
phi_ED:DR	0.05	0.02	0.01	0.09	2767	2747
Lepidosauria_19						
Intercept	-1.91	0.05	-2.00	-1.81	2881	2650
phi_Intercept	2.02	0.07	1.88	2.17	2663	2817
ED	0.61	0.09	0.43	0.79	1594	1711
DR	0.57	0.08	0.41	0.73	1578	1836
phi_ED	-0.66	0.13	-0.93	-0.40	1628	1518
phi_DR	-0.64	0.12	-0.87	-0.41	1606	1554
Mammalia_25						
Intercept	-0.74	0.11	-0.95	-0.53	2212	2634
phi_Intercept	1.12	0.14	0.85	1.40	2078	2429
ED	-0.59	0.12	-0.82	-0.37	2129	2184
DR	0.08	0.08	-0.08	0.24	2486	2485
ED:DR	-0.12	0.03	-0.17	-0.07	2387	2413
phi_ED	0.40	0.14	0.12	0.68	2300	2464
phi_DR	-0.12	0.10	-0.33	0.08	2376	2475
phi_ED:DR	0.11	0.04	0.04	0.18	2111	2507

Supplementary Table 4 | Median difference, median, and IQR of pEX for species with (1) and without (0) binary attributes (*n*>200) exhibiting >0.05 difference in pEX.

Trait	diff	med0	med1	IQR0	IQR1	n0	n1
BiomeNum_3	0.33	0.06	0.39	0.15	0.54	32977	293
Oceania	0.24	0.06	0.3	0.16	0.36	33035	235
BiomeNum_2	0.1	0.06	0.16	0.15	0.31	31816	1454
MajorHabitat_10	0.08	0.06	0.14	0.16	0.17	32719	343
Insularity	0.07	0.05	0.13	0.13	0.29	26601	6679
Aqu	0.06	0.05	0.11	0.14	0.28	27785	5496

Supplementary Table 5 | Comparison of mean lifetimes (years) from Monroe et al.[23] for empirical IUCN status changes in birds without conservation intervention (nC) and estimated from our pEX1 dataset (pEX1), with the difference and average of nC/pEX1 used in the Bland-Altman plots at *P*<0.05 (Extended Data Fig. 4).

	Birds only				All tetrapods		
Status	**nC**	**pEX1**	**diff**	**avg**	**pEX1**	**diff**	**avg**
LC	3347	8953	-5606	6150	7457	-4110	5402
NT	2161	2181	-20	2171	2108	53	2135
VU	1691	1693	-2	1692	1486	205	1589
EN	1371	1220	151	1296	921	450	1146
CR	1015	1009	6	1012	650	365	833
EW/EX	598	792	-194	695	501	97	550

Supplementary Table 6 | Phylogenetic independent contrasts comparing pEX ~ ED * DR for all species (Full model) and excluding outliers (Pruned model), showing redundance of phylogenetic comparative analysis (i.e., R^2 ~ 0 without outliers).

Term	Estimate	S.E.	T	P
Full model: All data				
(Intercept)	-0.005	0.006	-0.911	0.362
ED	-0.004	0.044	-0.096	0.924
DR	-0.62	0.032	-19.348	0
ED:DR	0.006	0.001	10.394	0
Note: $R^2 = 0.054$, Adjusted $R^2 = 0.053$, Model $p = <2e-16$				
Pruned model: Without outliers				
(Intercept)	0	0.003	-0.121	0.904
ED	0.166	0.055	3.031	0.002
DR	0.114	0.043	2.619	0.009
ED:DR	-0.028	0.028	-1.005	0.315
Note: $R^2 = 0$, Adjusted $R^2 = 0$, Model $p = 0.0098$				

Supplementary Table 7 | Expected species extinctions by Clade and overall, across a ~50–500-year time horizon in absolute and percentage terms, assuming current trajectories.

Clade	# Extinct	% Extinct
Amphibia	1693 (1653–1722)	23 (23–24)
Aves	966 (952–979)	10 (10–10)
Crocodylia	8 (7–9)	30 (26–33)
Lepidosauria	1329 (1303–1358)	14 (13–14)
Mammalia	1017 (995–1036)	17 (17–18)
Testudines	124 (117–127)	35 (33–36)
Tetrapoda	5139 (5029–5221)	15 (15–16)

Supplementary Table 8 | Factor loadings for PCA of attribute space (Fig. 3c, f; Extended Data Figure 9) under current conditions (PC1/2), weighted by extinction probability (pEX; PC1/2x), and by weighted by survival probability (1 - pEX; PC1/2f).

Factor	PC1	PC2	PC1x	PC2x	PC1f	PC2f
DirectDev	-0.23	0.22	0.87	-0.27	0.63	-0.66
LarvalStage	0.23	-0.22	-0.87	0.27	-0.63	0.66
LitterSize	0.23	-0.22	-0.88	0.27	-0.61	0.65
PC1	-0.21	0.2	0.79	-0.24	0.57	-0.59
EcoFresh	0.11	-0.26	-0.48	0.53	-0.26	0.72
EcosystemSum	0.07	-0.26	-0.38	0.59	-0.14	0.74
TempSeasonality	-0.21	-0.18	0.36	0.56	0.67	0.43
MajorHabitat_5	0.09	-0.25	-0.44	0.53	-0.22	0.71
BiomeNum_1	0.22	0.14	-0.38	-0.47	-0.7	-0.31
AnnuPrecip	0.22	0.13	-0.35	-0.5	-0.69	-0.28
AnnuMeanTemp	0.15	0.16	-0.14	-0.59	-0.49	-0.37
BodyLength_mm	-0.18	0.08	0.71	0.05	0.48	-0.27
BodyMass_g	-0.17	0.04	0.67	0.15	0.48	-0.13
Insularity	0.08	0.1	0.11	-0.37	-0.3	-0.23
PropGrazingArea	-0.11	-0.07	0.02	0.26	0.38	0.15
Elevation	-0.03	-0.07	-0.24	0.26	0.15	0.13

Supplementary References

1. Moura, M. R. *et al.* A phylogeny-informed characterisation of global tetrapod traits addresses data gaps and biases. *PLOS Biology* **22**, e3002658 (2024).
2. Bird, J. P. *et al.* Generation lengths of the world's birds and their implications for extinction risk. *Conservation Biology* **34**, 1252–1261 (2020).
3. De Magalhães, J. P. & Costa, J. A database of vertebrate longevity records and their relation to other life-history traits. *Journal of Evolutionary Biology* **22**, 1770–1774 (2009).
4. Jetz, W., Sekercioglu, C. H. & Böhning-Gaese, K. The Worldwide Variation in Avian Clutch Size across Species and Space. *PLOS Biology* **6**, e303 (2008).
5. Jones, K. E. *et al.* PanTHERIA: a species-level database of life history, ecology, and geography of extant and recently extinct mammals. *Ecology* **90**, 2648–2648 (2009).
6. Maiorano, L., Montemaggiori, A., Ficetola, G. F., O'Connor, L. & Thuiller, W. TETRA-EU 1.0: A species-level trophic metaweb of European tetrapods. *Global Ecology and Biogeography* **29**, 1452–1457 (2020).
7. Meiri, S. SquamBase—A database of squamate (Reptilia: Squamata) traits. *Global Ecology and Biogeography* **33**, e13812 (2024).
8. Myhrvold, N. P. *et al.* An amniote life-history database to perform comparative analyses with birds, mammals, and reptiles. *Ecology* **96**, 3109–3109 (2015).
9. Oliveira, B. F., São-Pedro, V. A., Santos-Barrera, G., Penone, C. & Costa, G. C. AmphiBIO, a global database for amphibian ecological traits. *Scientific Data* **4**, 1–7 (2017).
10. Oskyrko, O., Mi, C., Meiri, S. & Du, W. ReptTraits: a comprehensive dataset of ecological traits in reptiles. *Sci Data* **11**, 243 (2024).

11. Pincheira-Donoso, D. *et al.* The global macroecology of brood size in amphibians reveals a predisposition of low-fecundity species to extinction. *Global Ecology and Biogeography* **30**, 1299–1310 (2021).

12. Ricklefs, R. E. Life-history connections to rates of aging in terrestrial vertebrates. *Proceedings of the National Academy of Sciences* **107**, 10314–10319 (2010).

13. Title, P. O. *et al.* The macroevolutionary singularity of snakes. *Science* **383**, 918–923 (2024).

14. Wilman, H. *et al.* EltonTraits 1.0: Species-level foraging attributes of the world's birds and mammals. *Ecology* **95**, 2027–2027 (2014).

15. Lintulaakso, K., Tatti, N. & Žliobaitė, I. Quantifying mammalian diets. *Mamm Biol* **103**, 53–67 (2023).

16. O'Connor, L. M. J. *et al.* Unveiling the food webs of tetrapods across Europe through the prism of the Eltonian niche. *Journal of Biogeography* **47**, 181–192 (2020).

17. Lopes, L. E., Fernandes, A. M. & Marini, M. Â. Predation on vertebrates by Neotropical passerine birds. *Lundiana* **6**, 57–66 (2005).

18. Liedtke, H. C., Wiens, J. J. & Gomez-Mestre, I. The evolution of reproductive modes and life cycles in amphibians. *Nat Commun* **13**, 7039 (2022).

19. Chamberlain, S. rredlist:"IUCN" red list client. *R package version 0.7. 0. See https://CRAN. Rproject. org/package= rredlist* (2020).

20. Dinerstein, E. *et al.* An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. *BioScience* **67**, 534–545 (2017).

21. Lilljeborg, W. Description of Halcrosia afzelii*: a new Crocodile from Sierra Leone, West Africa. *Proceedings of the Zoological Society of London* **1867**, 715–718 (1867).

22. Anonymous. *International Code of Zoological Nomenclature*. (International Trust for Zoological Nomenclature, c/o Natural History Museum, London, U.K., 1999).

23. Monroe, M. J., Butchart, S. H. M., Mooers, A. O. & Bokma, F. The dynamics underlying avian extinction trajectories forecast a wave of extinctions. *Biology Letters* **15**, 20190633 (2019).