

Supplementary Information

Dinosaur biodiversity declined well before the asteroid impact, influenced by ecological and environmental pressures

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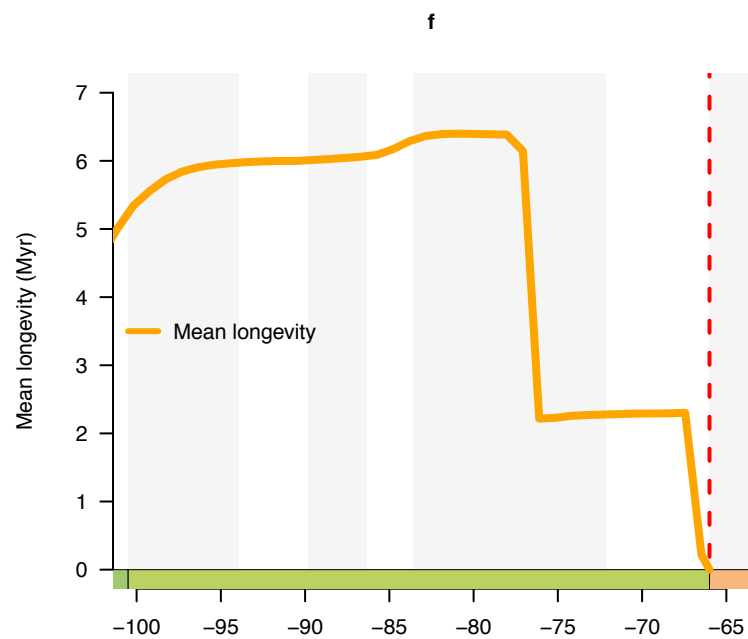
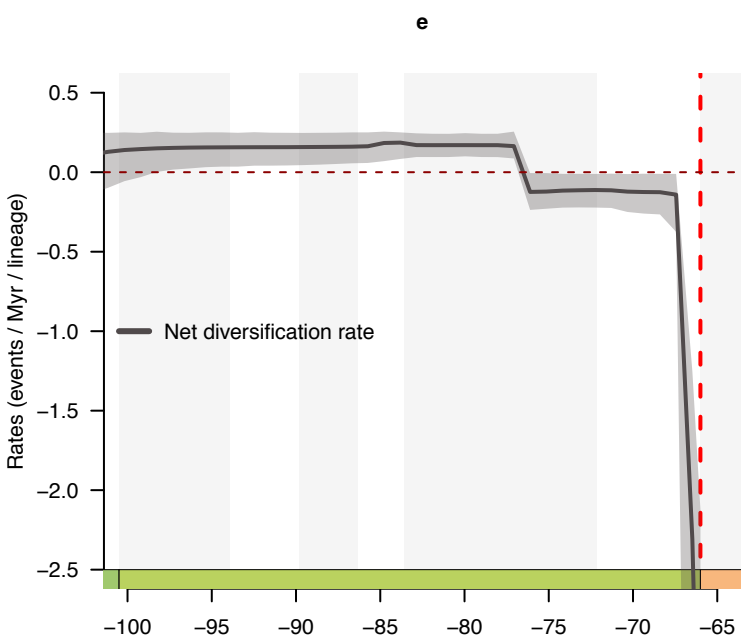
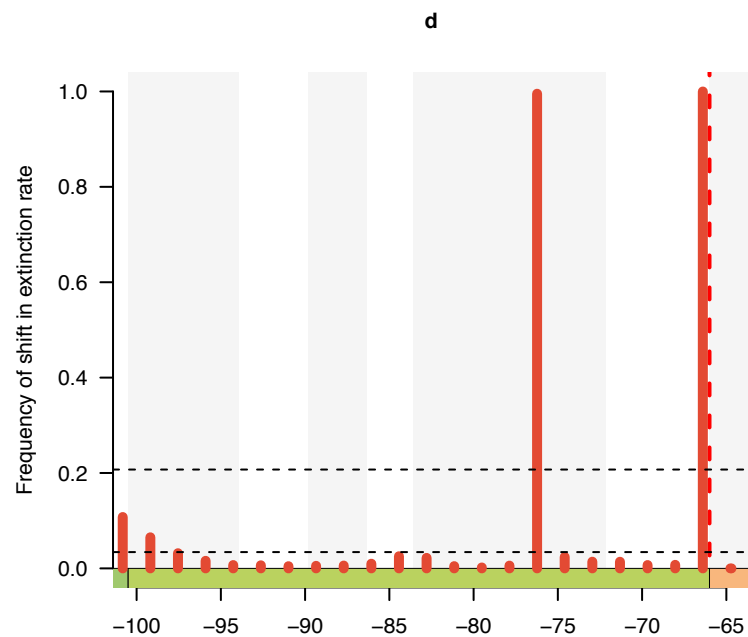
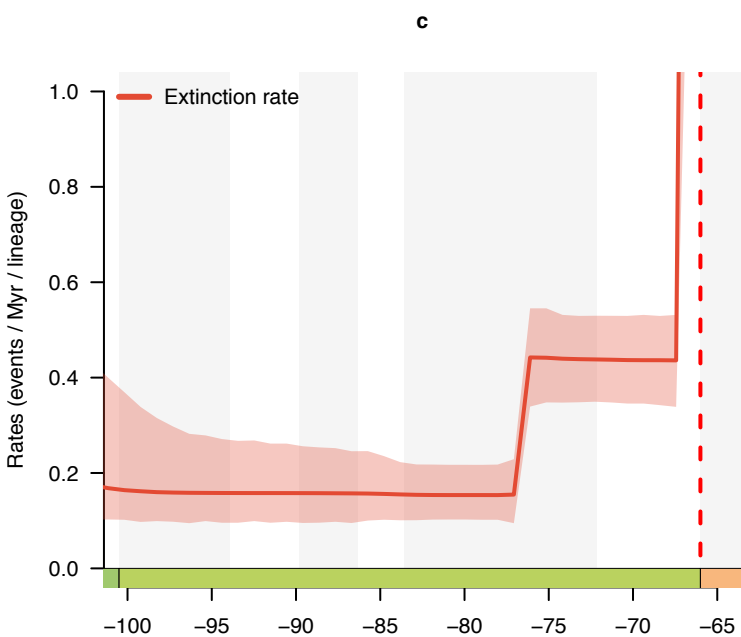
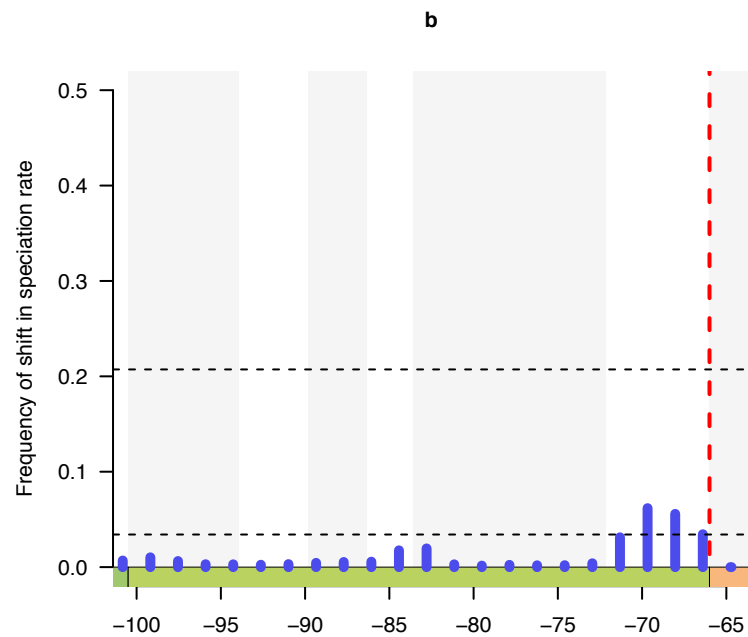
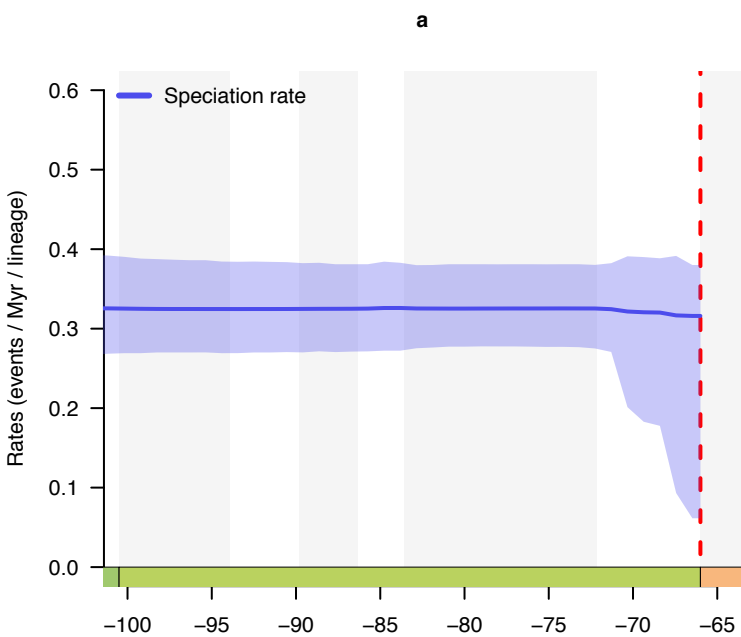
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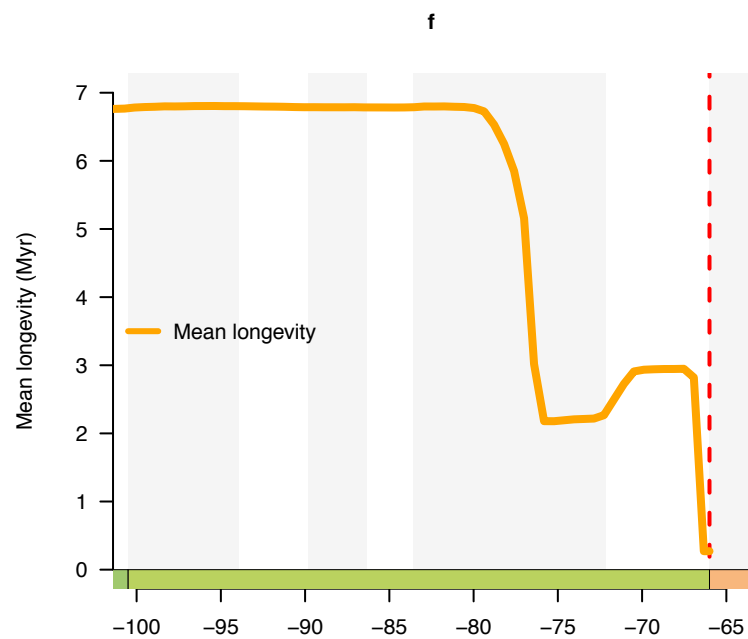
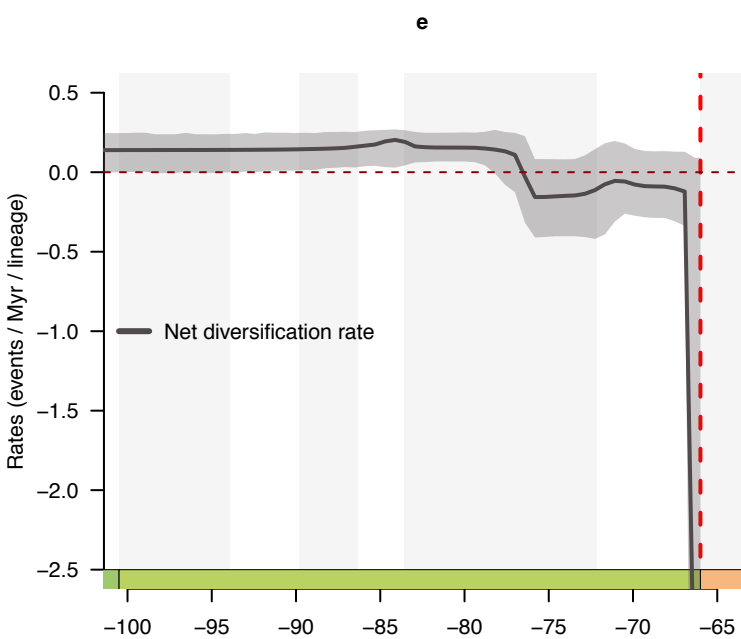
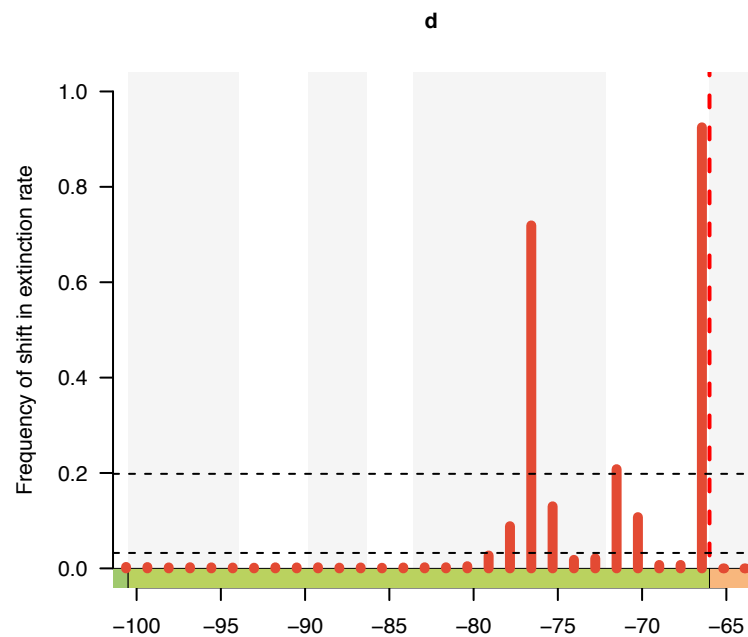
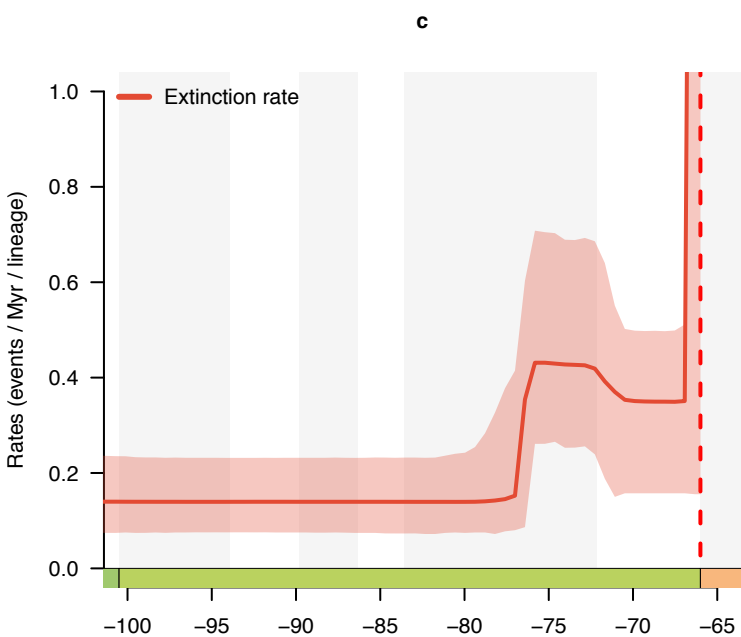
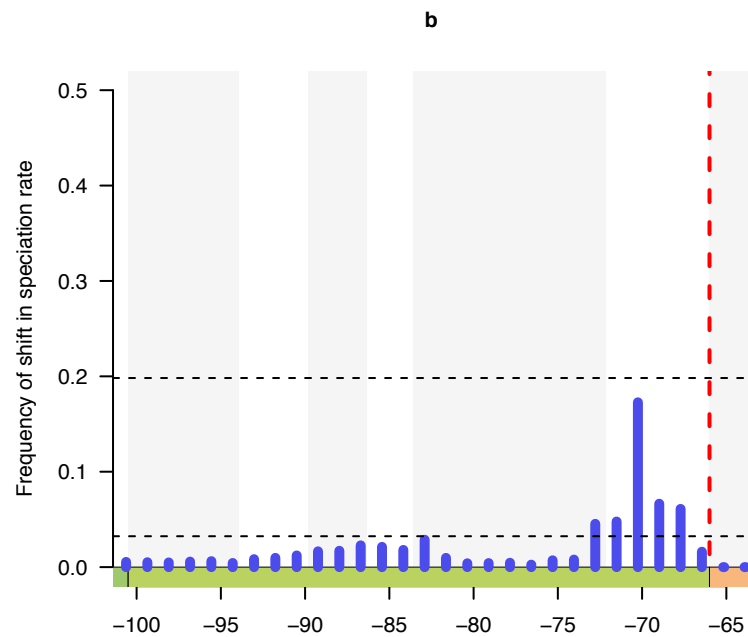
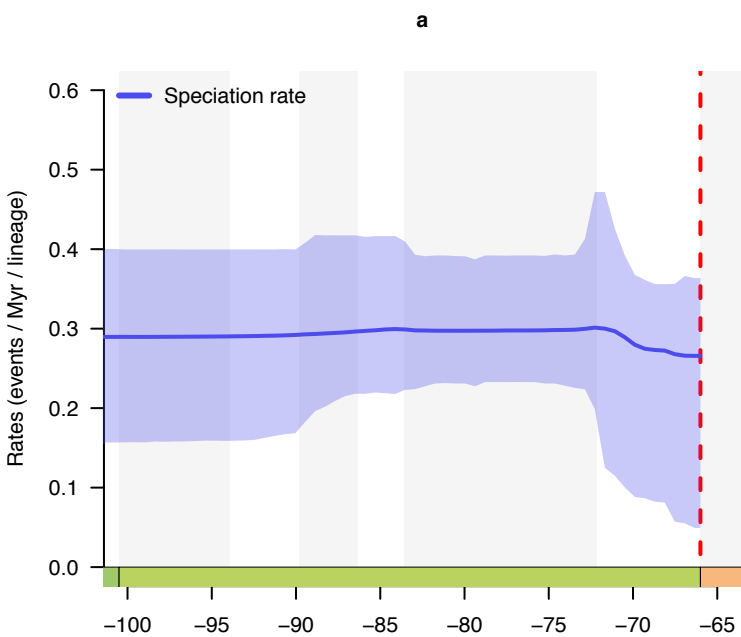
These authors jointly supervised this work: Michael J. Benton, Philip J. Currie.

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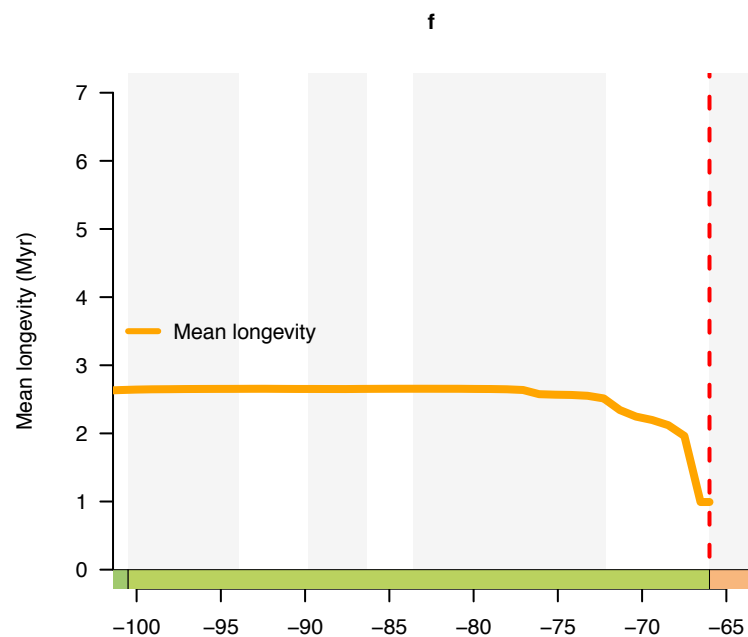
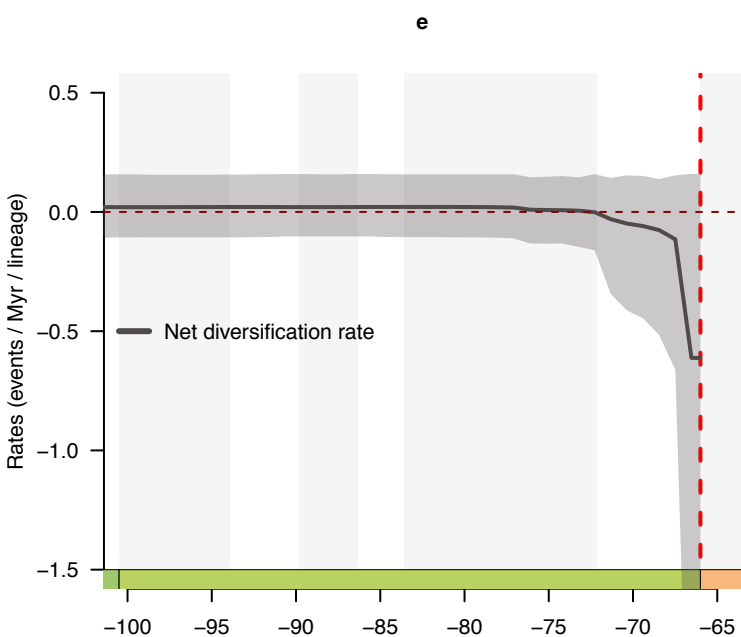
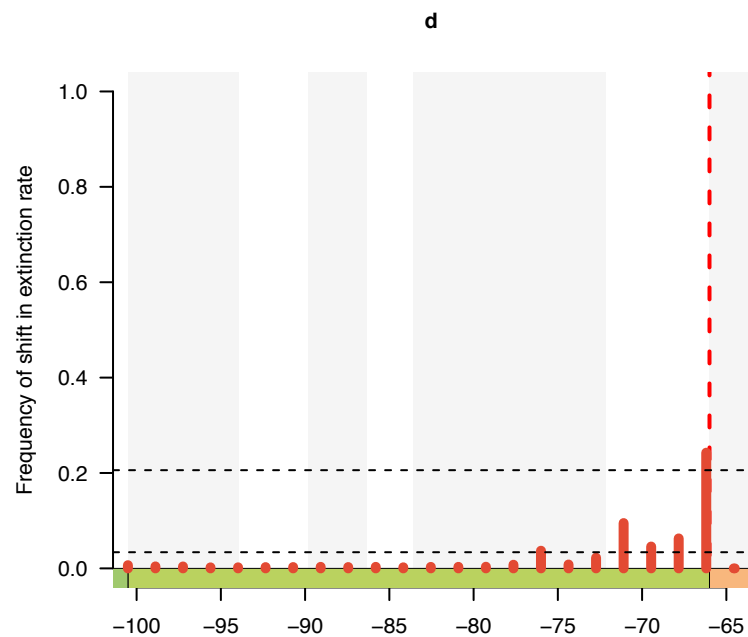
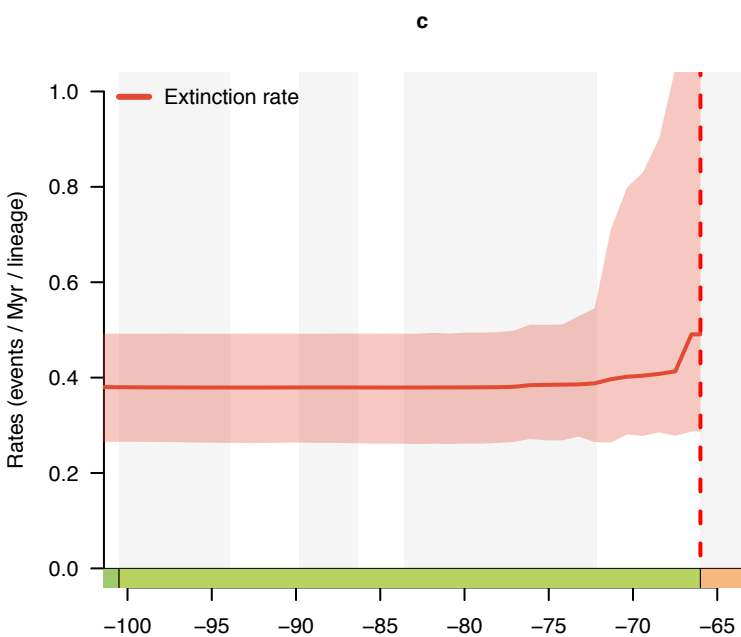
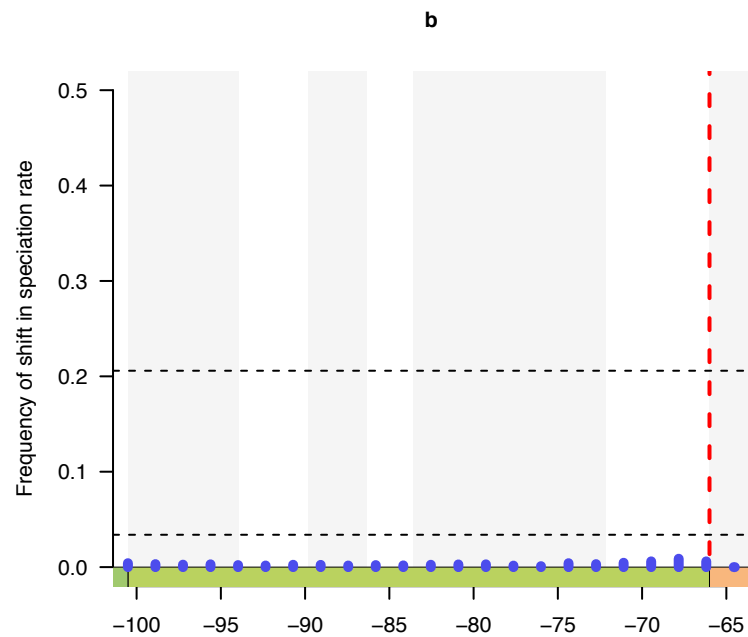
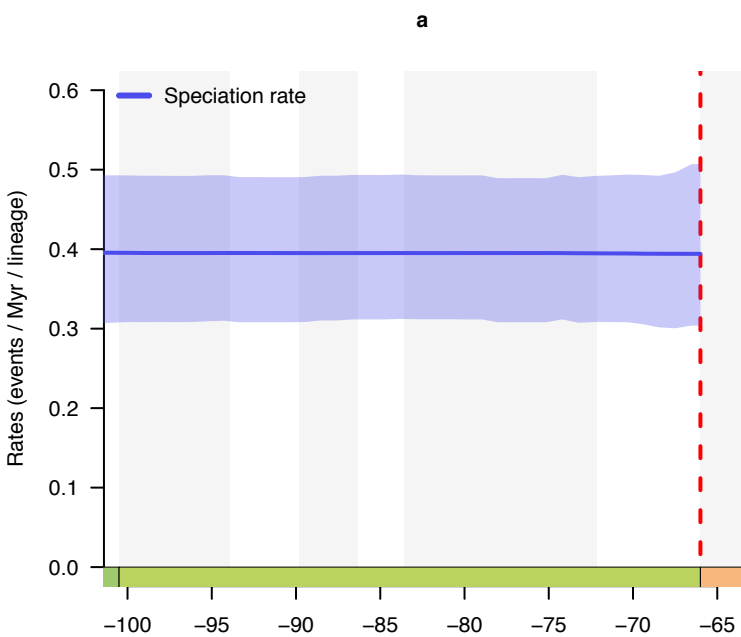
Supplementary Figure 1. Diversification and diversity dynamics of Late Cretaceous dinosaurs. The Bayesian RJMCMC model estimates speciation rate (**a**), time shifts in speciation rate (**b**), extinction rate (**c**), time shifts in extinction rate (**d**), net diversification rate (**e**, speciation minus extinction) rates, and species longevity in million years (**f**). Solid lines indicate mean posterior rates and shaded areas show 95% CI. As in the BDMCMC model, net diversification decreased and became negative ~76 Myrs ago (late Campanian). The vertical dashed red line indicates the Cretaceous-Palaeogene mass extinction (66 Myrs ago).



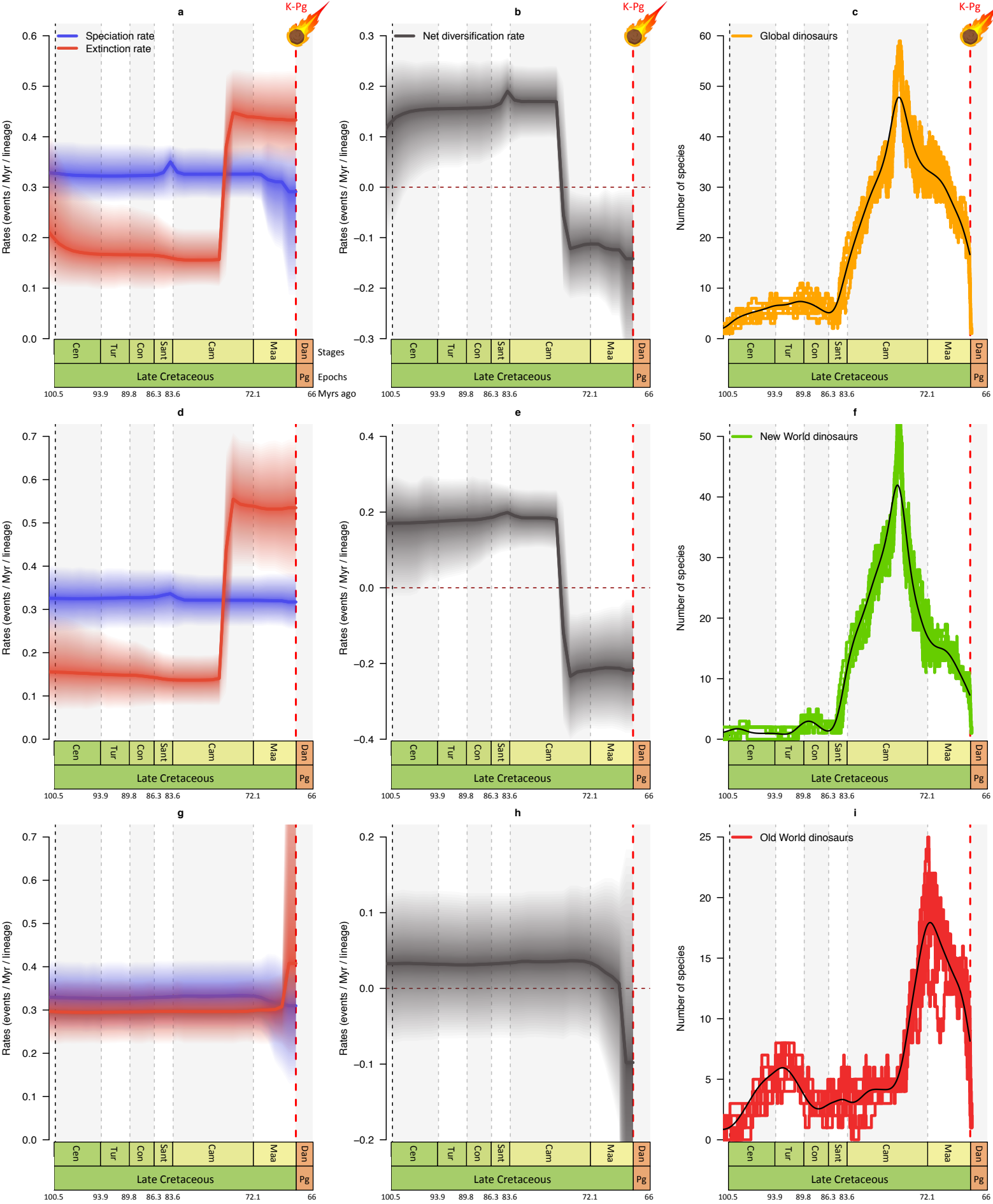
Supplementary Figure 2. Diversification and diversity dynamics of Late Cretaceous herbivorous dinosaurs. The Bayesian RJMCMC model estimates speciation rate (**a**), time shifts in speciation rate (**b**), extinction rate (**c**), time shifts in extinction rate (**d**), net diversification rate (**e**, speciation minus extinction) rates, and species longevity in million years (**f**). Solid lines indicate mean posterior rates and shaded areas show 95% CI. As in the BDMCMC model, net diversification decreased and became negative ~76 Myrs ago (late Campanian). The vertical dashed red line indicates the Cretaceous-Palaeogene mass extinction (66 Myrs ago).



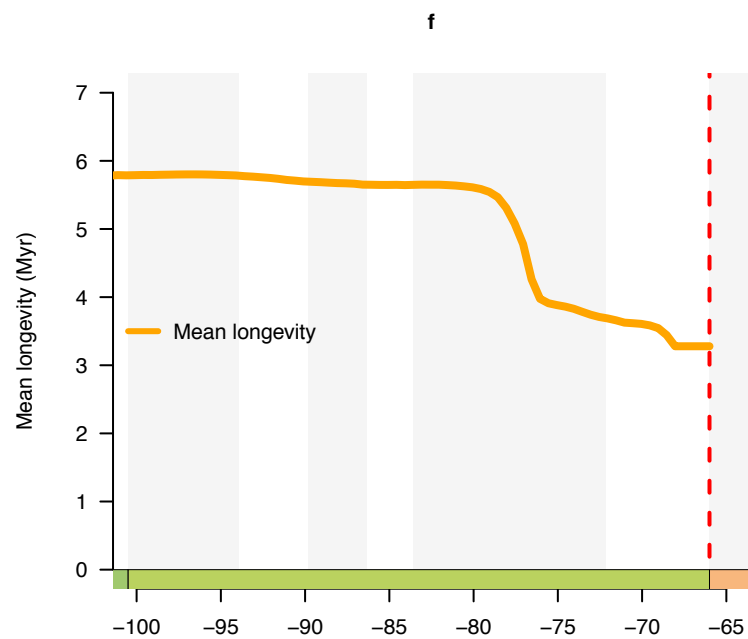
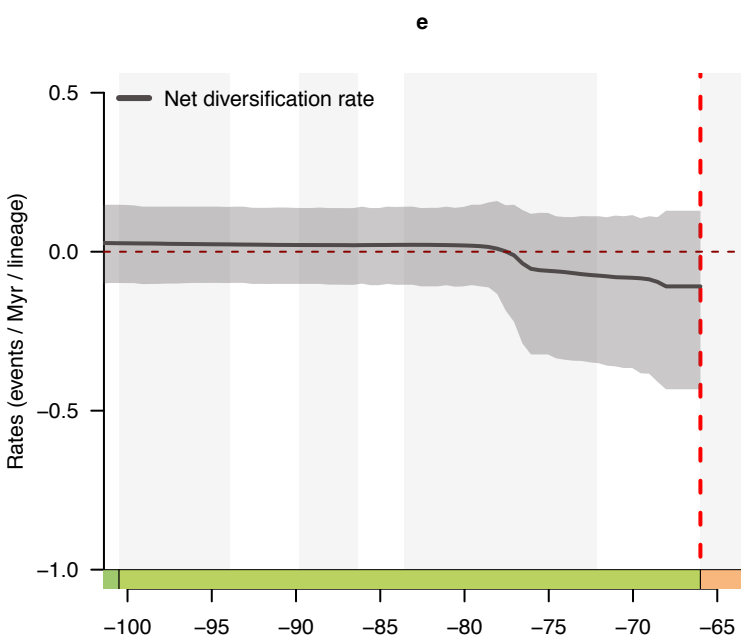
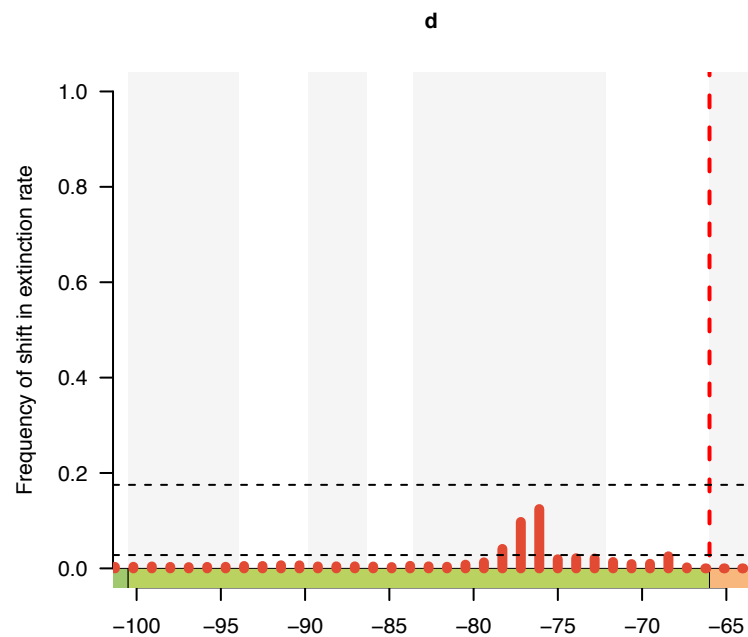
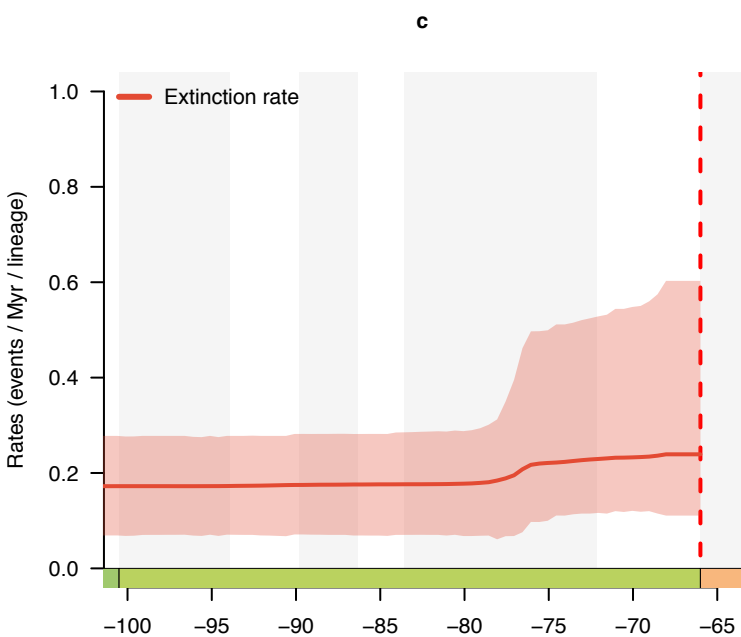
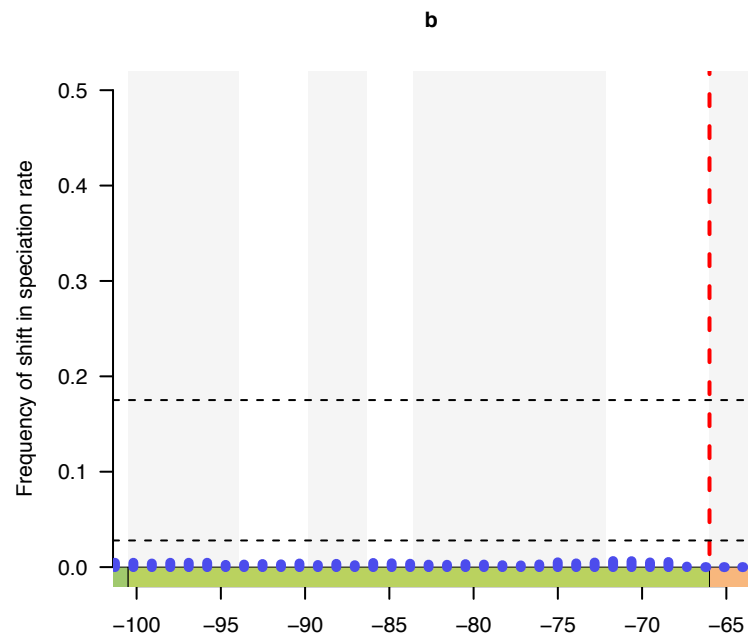
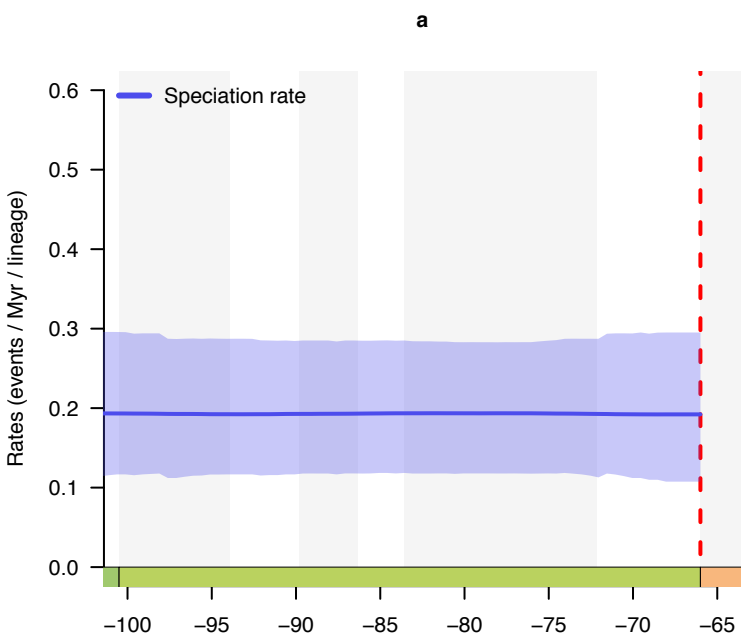
Supplementary Figure 3. Diversification and diversity dynamics of Late Cretaceous carnivorous dinosaurs. The Bayesian RJMCMC model estimates speciation rate (**a**), time shifts in speciation rate (**b**), extinction rate (**c**), time shifts in extinction rate (**d**), net diversification rate (**e**, speciation minus extinction) rates, and species longevity in million years (**f**). Solid lines indicate mean posterior rates and shaded areas show 95% CI. As in the BDMCMC model, net diversification decreased and became negative ~72 Myrs ago (early Maastrichtian). The vertical dashed red line indicates the Cretaceous-Palaeogene mass extinction (66 Myrs ago).



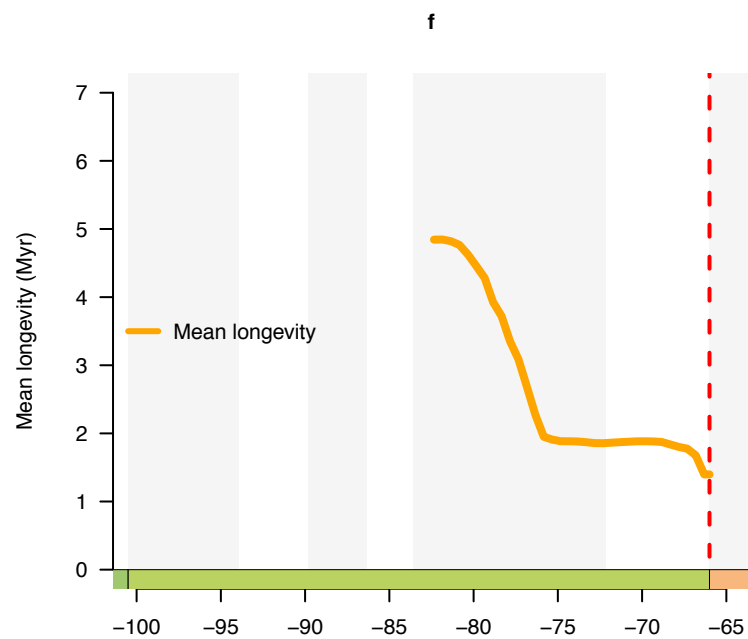
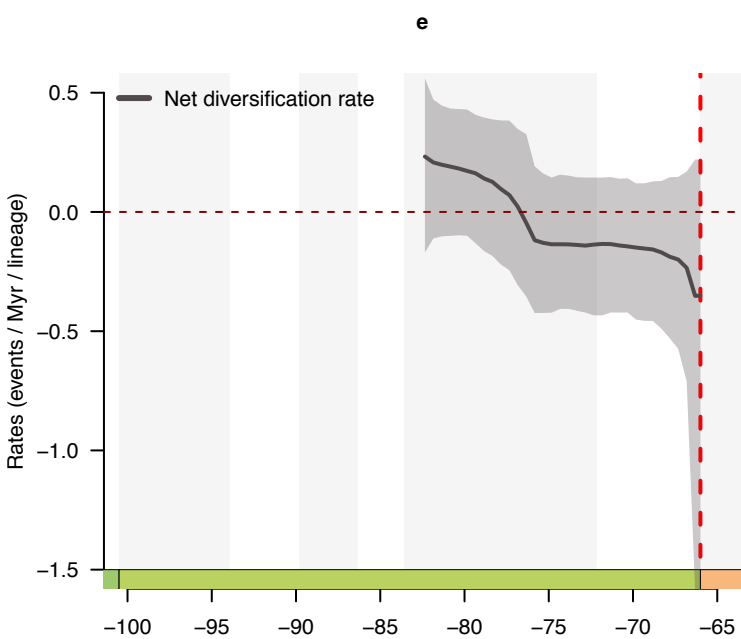
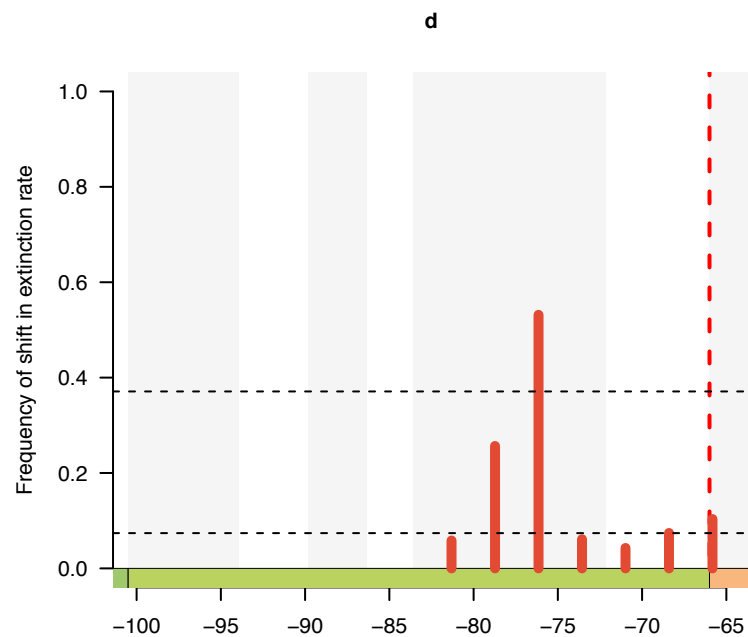
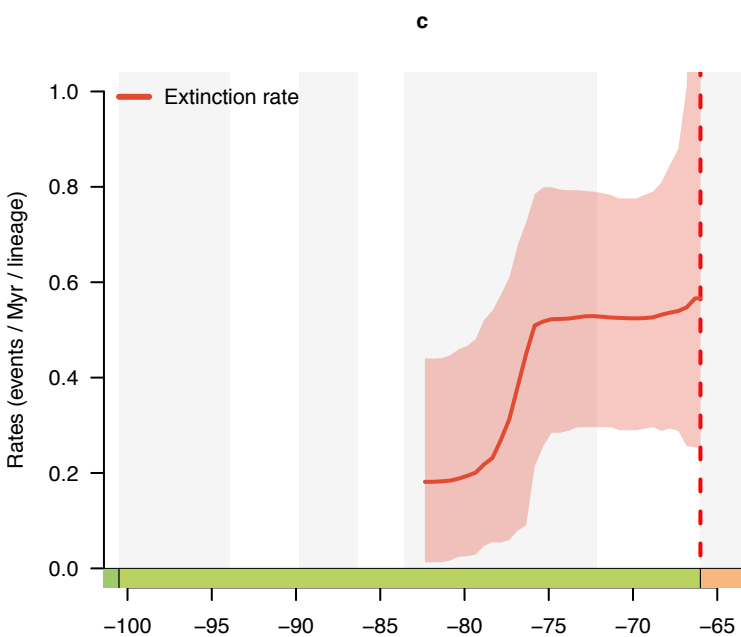
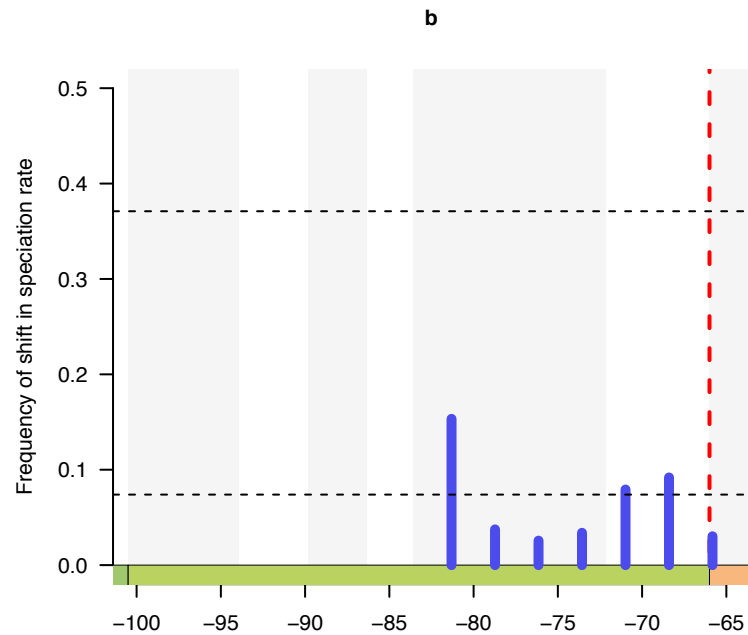
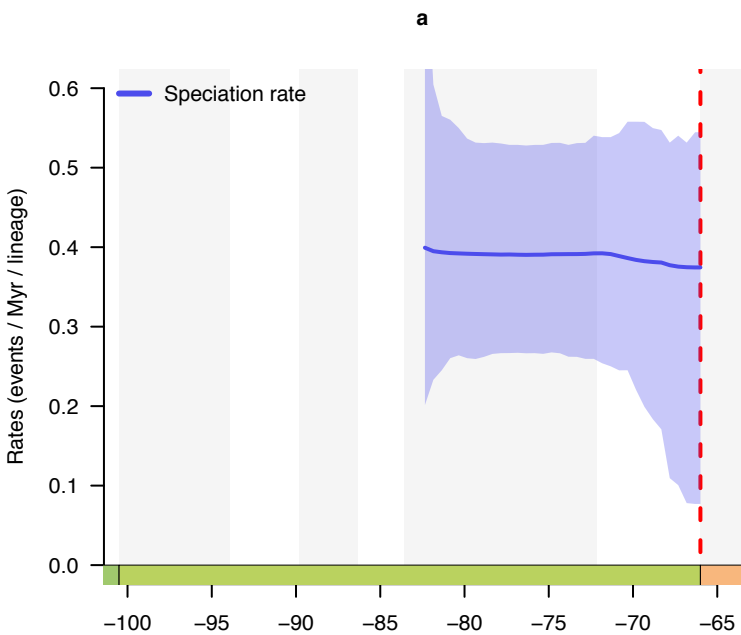
Supplementary Figure 4. Diversification and diversity dynamics of Late Cretaceous dinosaurs. The Bayesian BDMCMC model estimates speciation and extinction rates (**a**), net diversification rate (**b**, speciation minus extinction) rates, and species diversity dynamics (**c**) for all dinosaur families at a global scale. The same results are shown for the New World dinosaurs (**d, e, and f**), and for the Old World dinosaurs (**g, h, and i**). Solid lines indicate mean posterior rates and shaded areas show 95% CI. The net diversification decreased and became negative in the late Campanian for the New World dinosaurs and in the early Maastrichtian for the Old World dinosaurs. Both the New World and Old World dinosaurs were in decline before the Cretaceous-Palaeogene (K-Pg) mass extinction (66 Myrs ago), represented by a vertical dashed red line. Asteroid icon made by Fabien Condamine.



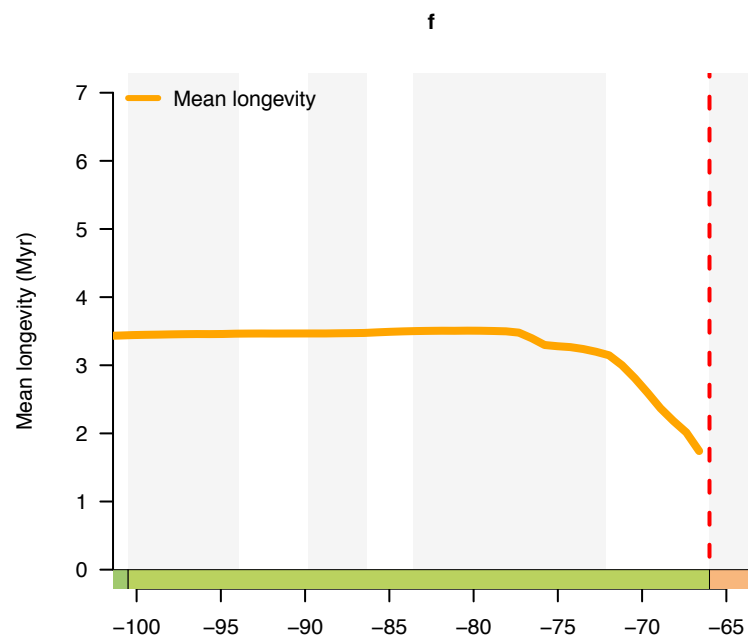
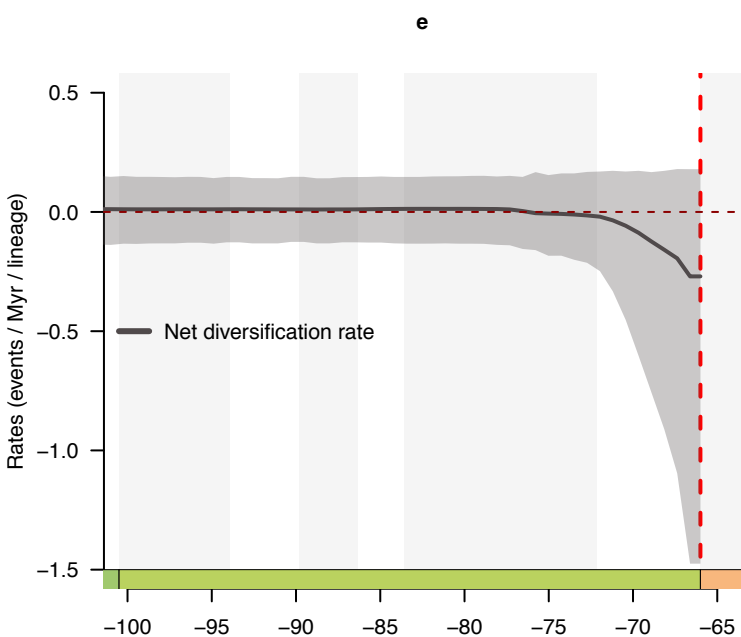
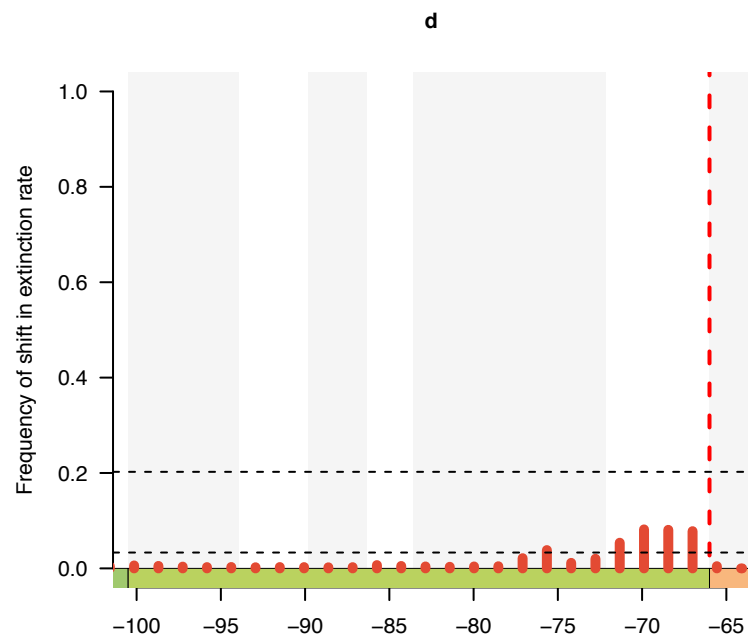
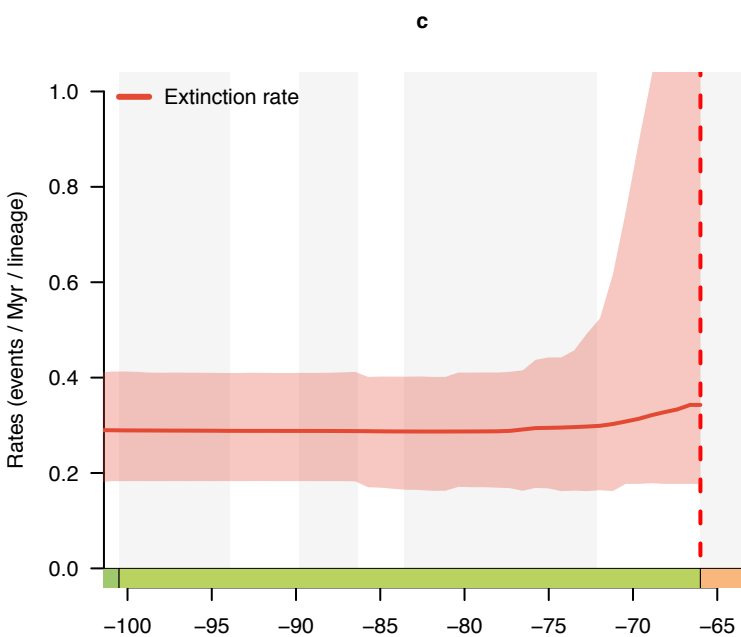
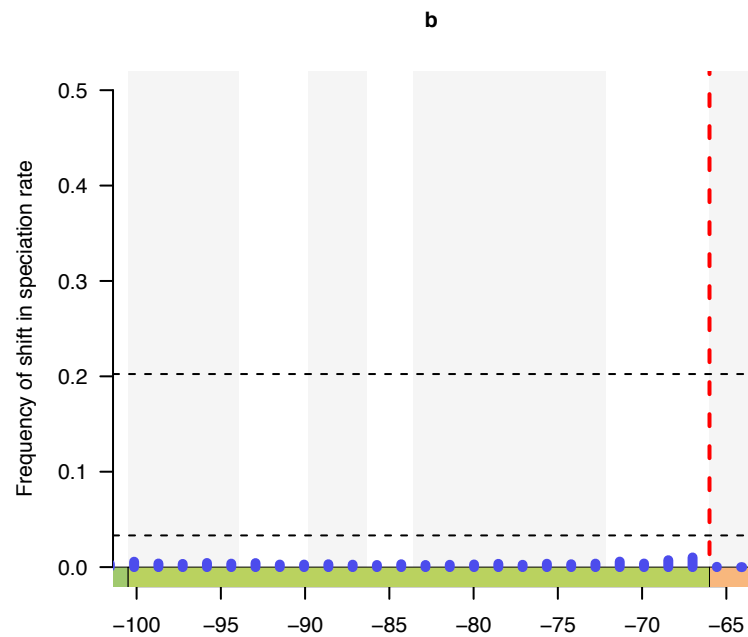
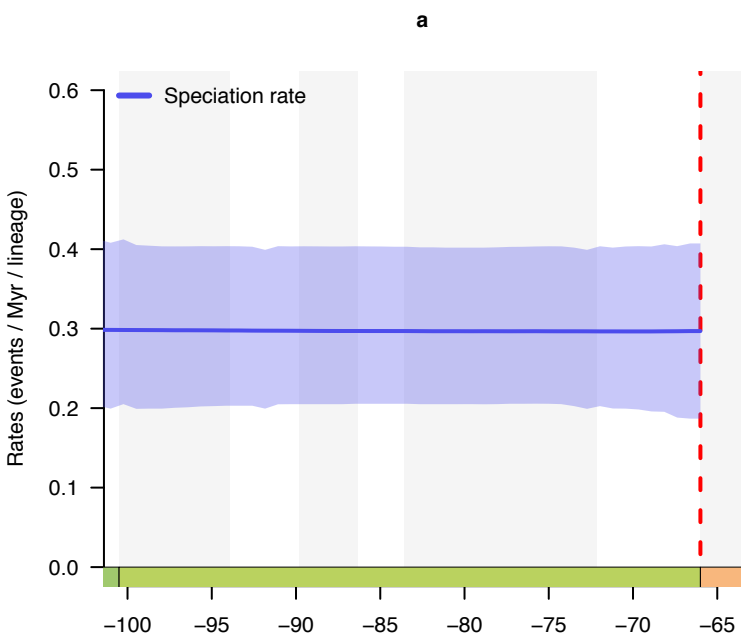
Supplementary Figure 5. Diversification and diversity dynamics of Late Cretaceous ankylosaurs. The Bayesian RJMCMC model estimates speciation rate (**a**), time shifts in speciation rate (**b**), extinction rate (**c**), time shifts in extinction rate (**d**), net diversification rate (**e**, speciation minus extinction) rates, and species longevity in million years (**f**). Solid lines indicate mean posterior rates and shaded areas show 95% CI. As in the BDMCMC model, net diversification decreased and became negative ~76 Myrs ago (late Campanian), mostly due to an increase of extinction rate. The vertical dashed red line indicates the Cretaceous-Palaeogene mass extinction (66 Myrs ago).



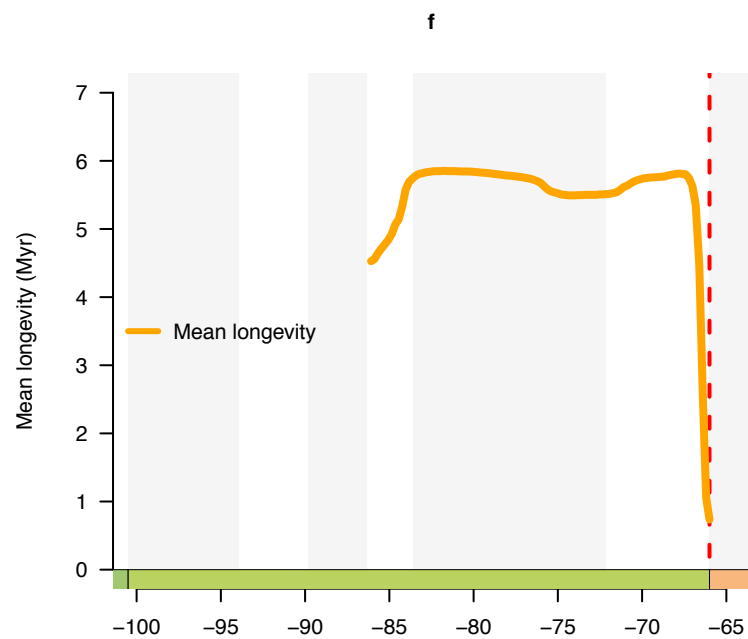
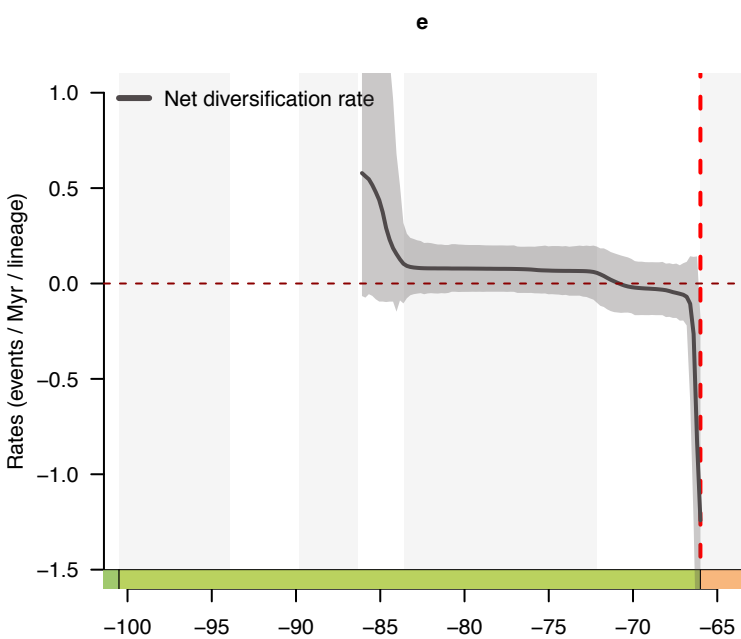
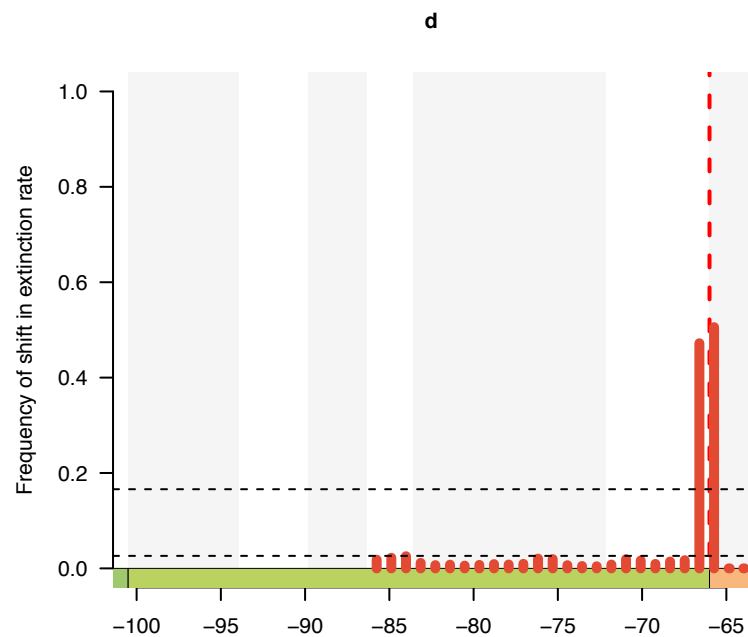
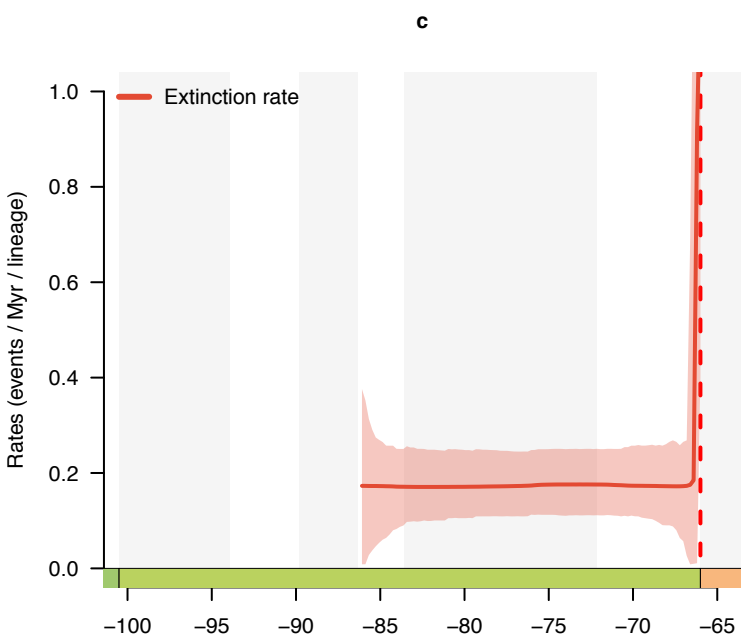
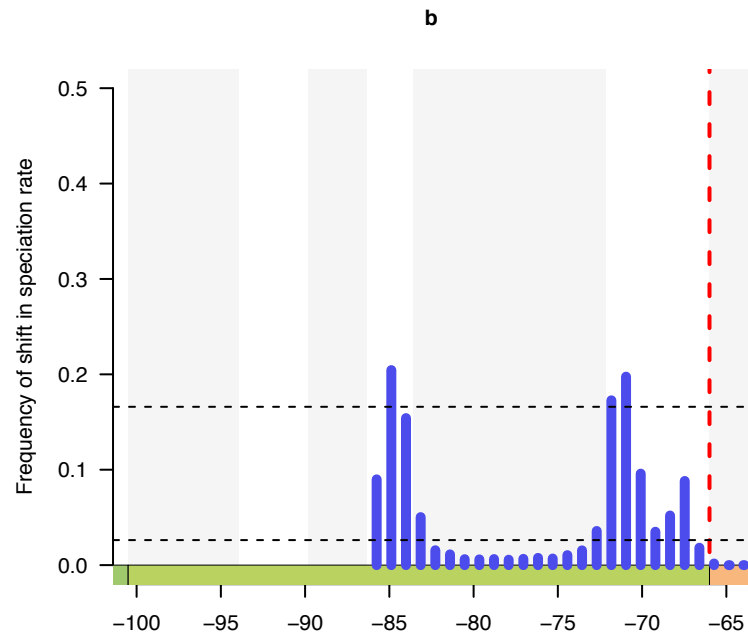
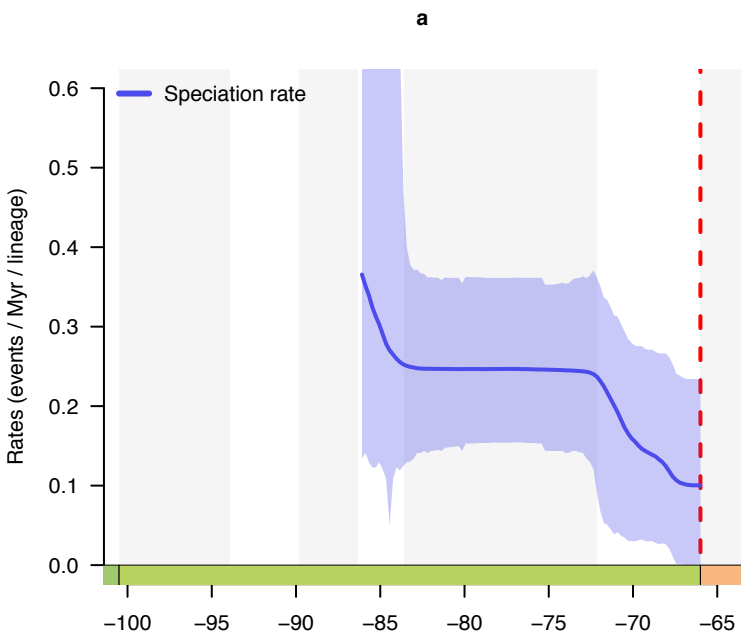
Supplementary Figure 6. Diversification and diversity dynamics of Late Cretaceous ceratopsians. The Bayesian RJMCMC model estimates speciation rate (**a**), time shifts in speciation rate (**b**), extinction rate (**c**), time shifts in extinction rate (**d**), net diversification rate (**e**, speciation minus extinction) rates, and species longevity in million years (**f**). Solid lines indicate mean posterior rates and shaded areas show 95% CI. As in the BDMCMC model, net diversification decreased and became negative ~76 Myrs ago (late Campanian), mostly due to an increase of extinction rate. The vertical dashed red line indicates the Cretaceous-Palaeogene mass extinction (66 Myrs ago).



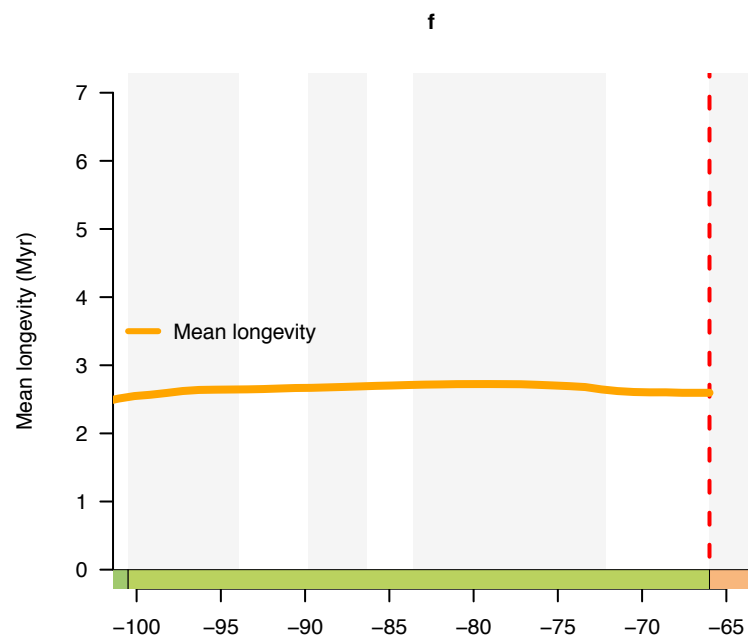
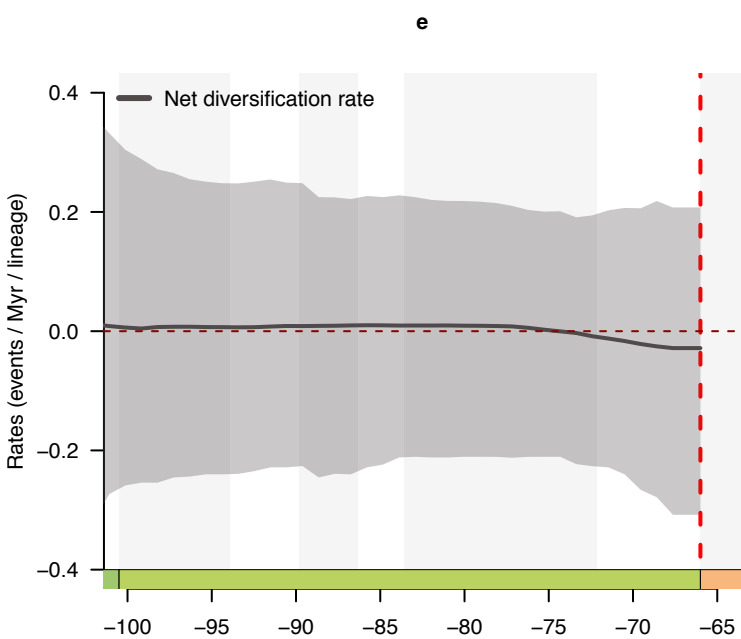
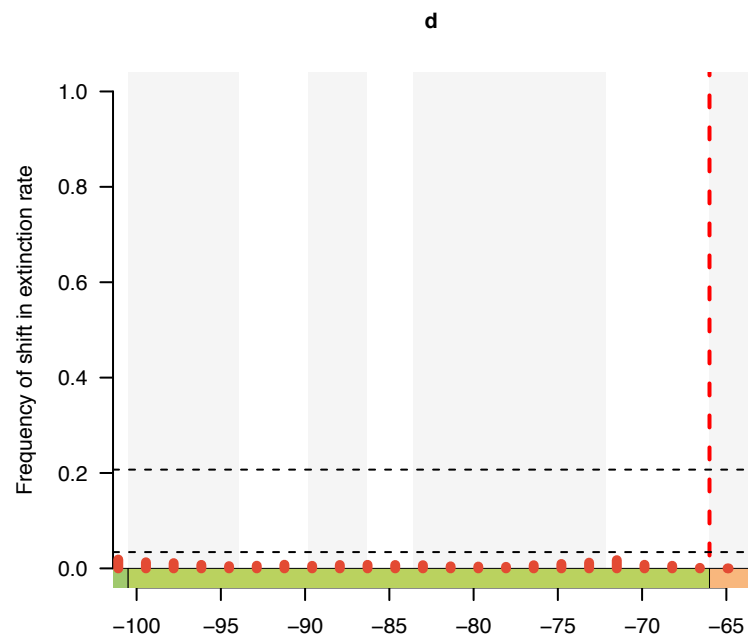
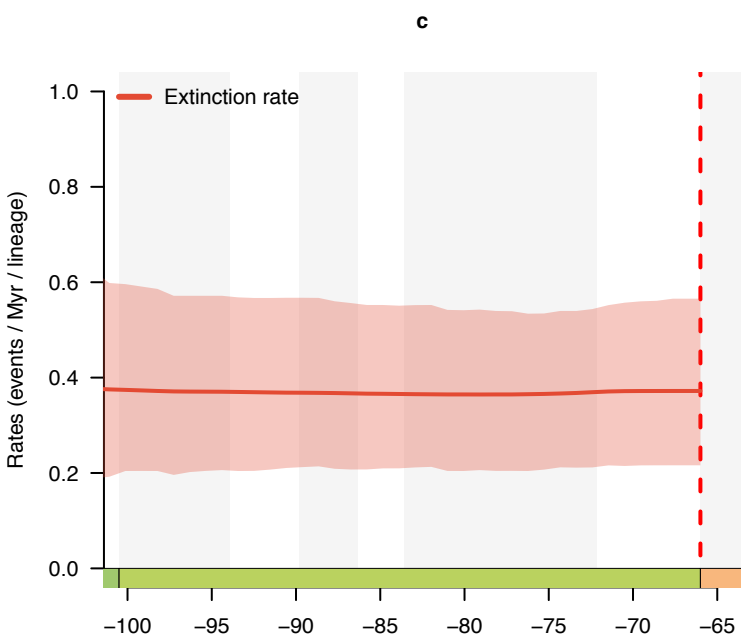
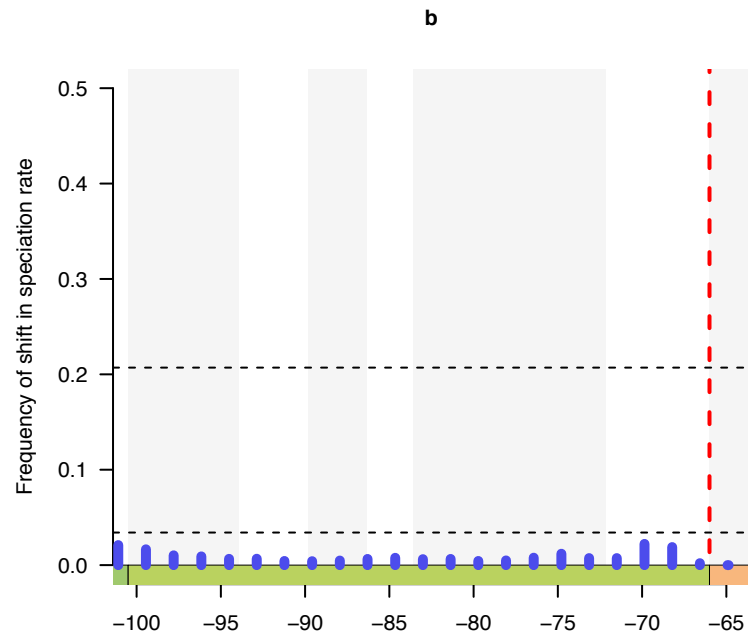
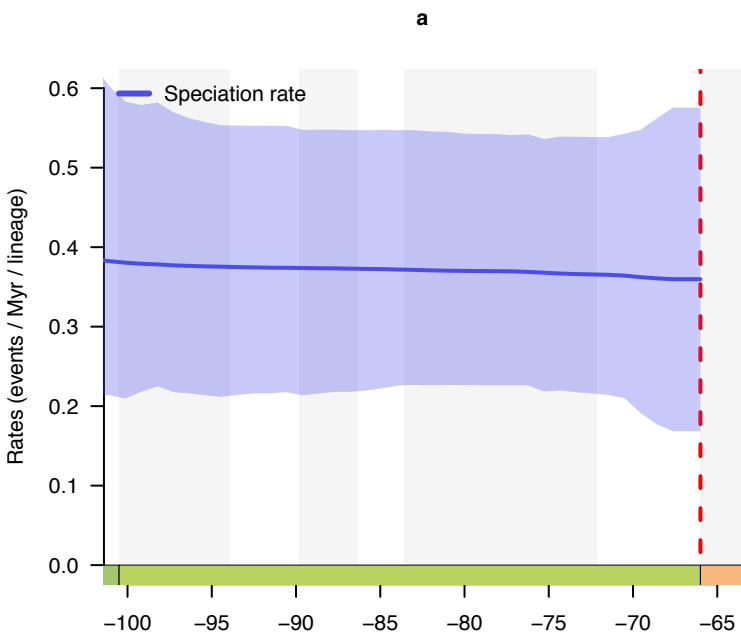
Supplementary Figure 7. Diversification and diversity dynamics of Late Cretaceous dromaeosaurs. The Bayesian RJMCMC model estimates speciation rate (**a**), time shifts in speciation rate (**b**), extinction rate (**c**), time shifts in extinction rate (**d**), net diversification rate (**e**, speciation minus extinction) rates, and species longevity in million years (**f**). Solid lines indicate mean posterior rates and shaded areas show 95% CI. As in the BDMCMC model, net diversification decreased and became negative ~72 Myrs ago (early Maastrichtian), mostly due to an increase of extinction rate. The vertical dashed red line indicates the Cretaceous-Palaeogene mass extinction (66 Myrs ago).



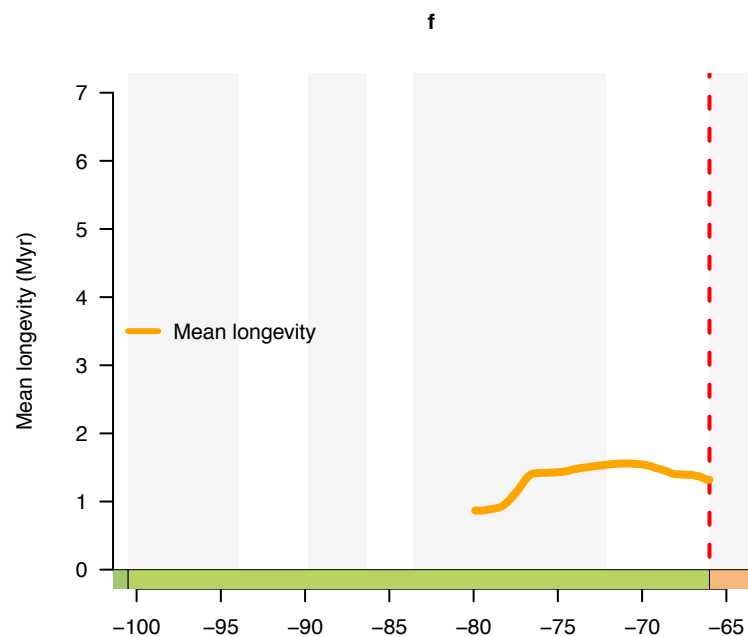
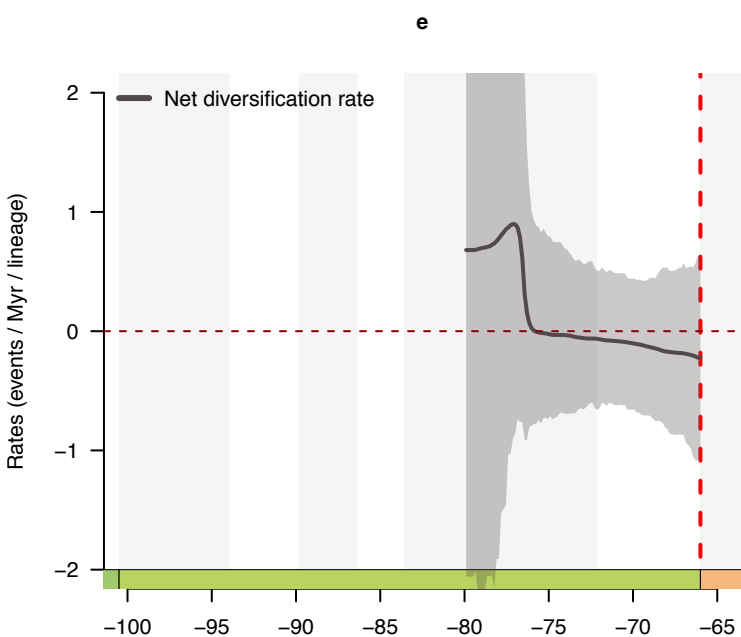
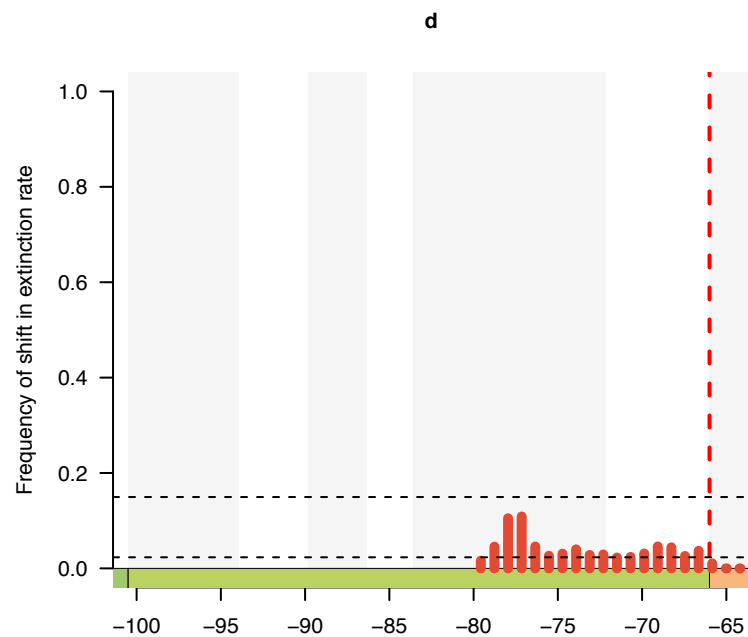
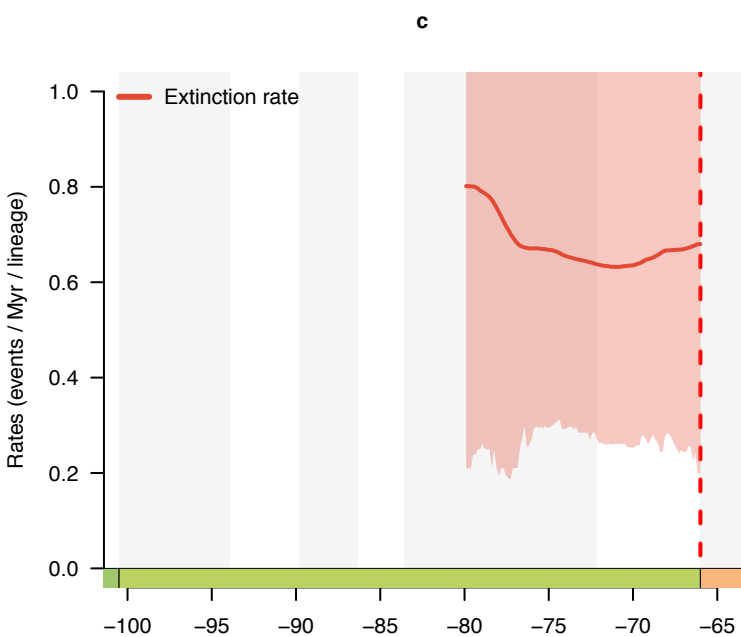
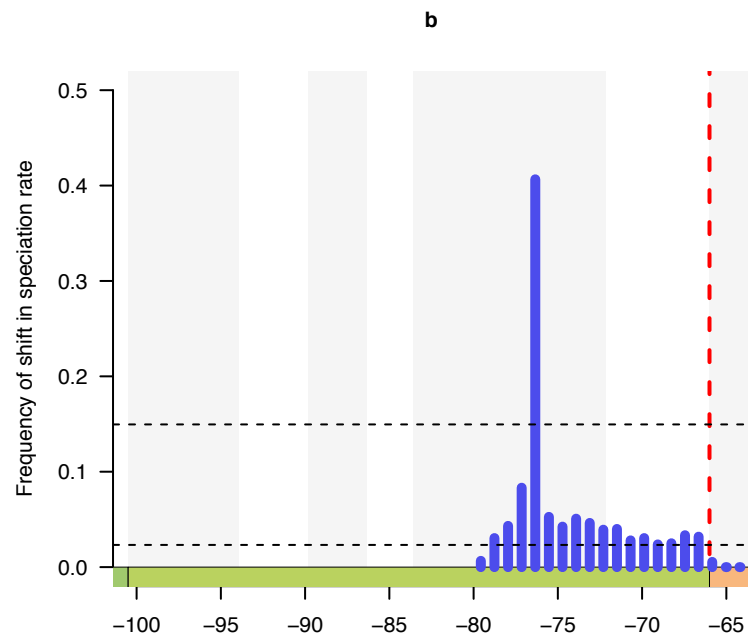
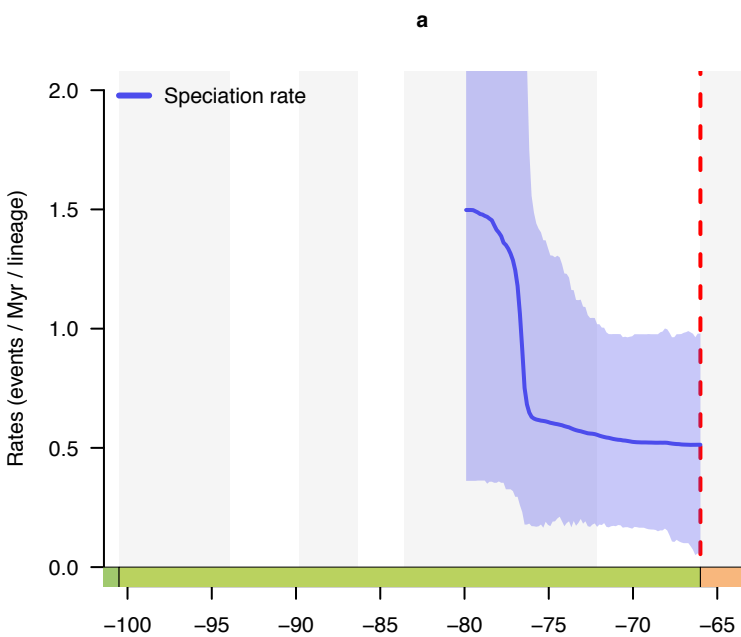
Supplementary Figure 8. Diversification and diversity dynamics of Late Cretaceous hadrosaurs. The Bayesian RJMCMC model estimates speciation rate (**a**), time shifts in speciation rate (**b**), extinction rate (**c**), time shifts in extinction rate (**d**), net diversification rate (**e**, speciation minus extinction) rates, and species longevity in million years (**f**). Solid lines indicate mean posterior rates and shaded areas show 95% CI. As in the BDMCMC model, net diversification decreased and became negative ~70 Myrs ago (middle Maastrichtian), mostly due to an decrease of speciation rate. The vertical dashed red line indicates the Cretaceous-Palaeogene mass extinction (66 Myrs ago).



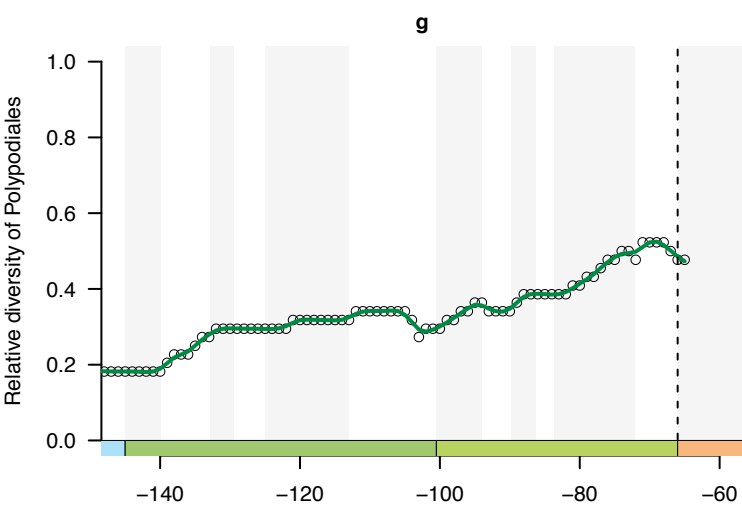
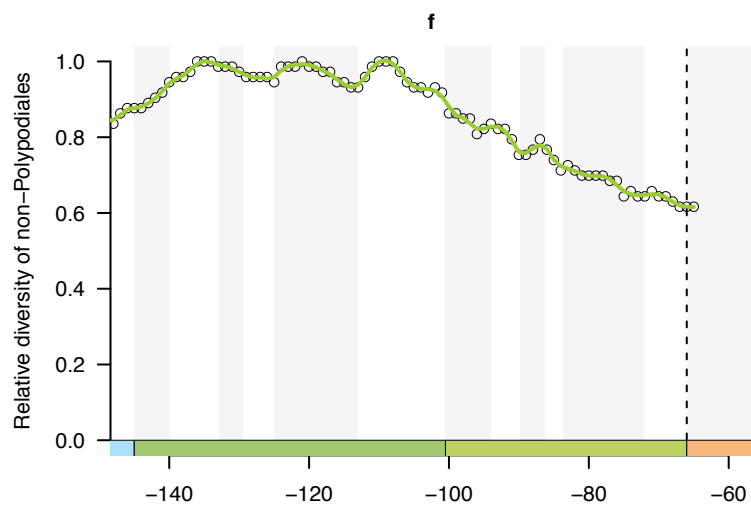
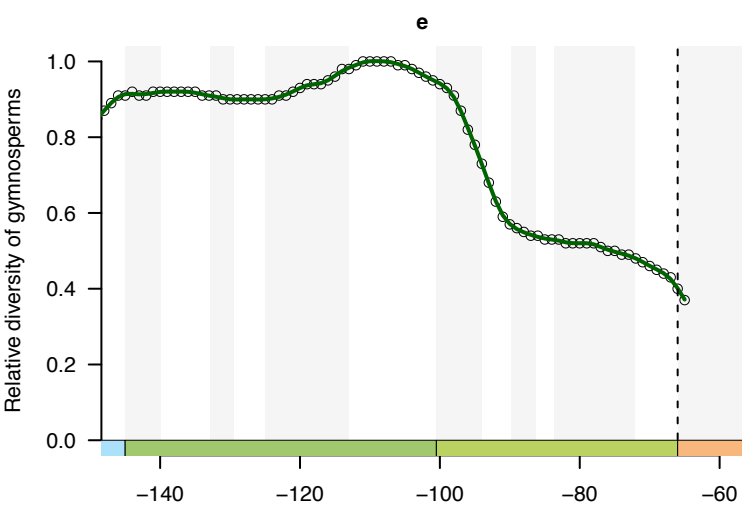
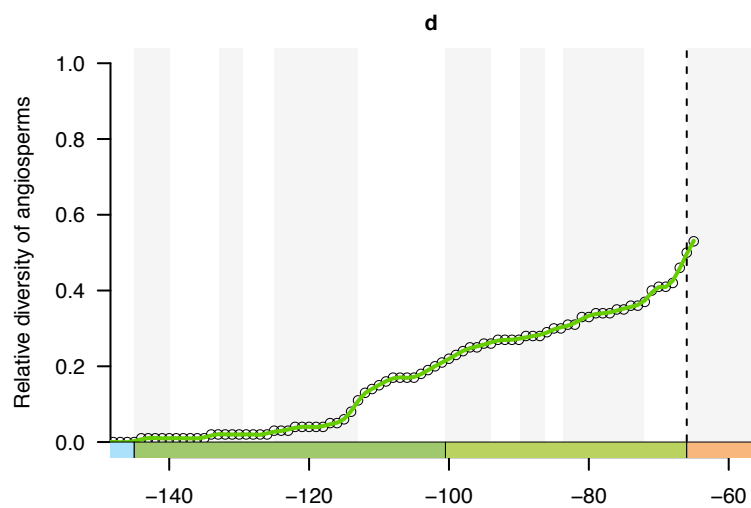
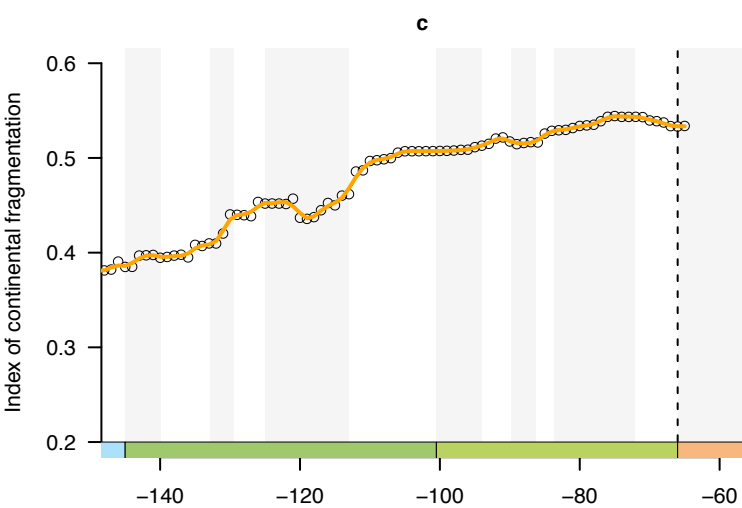
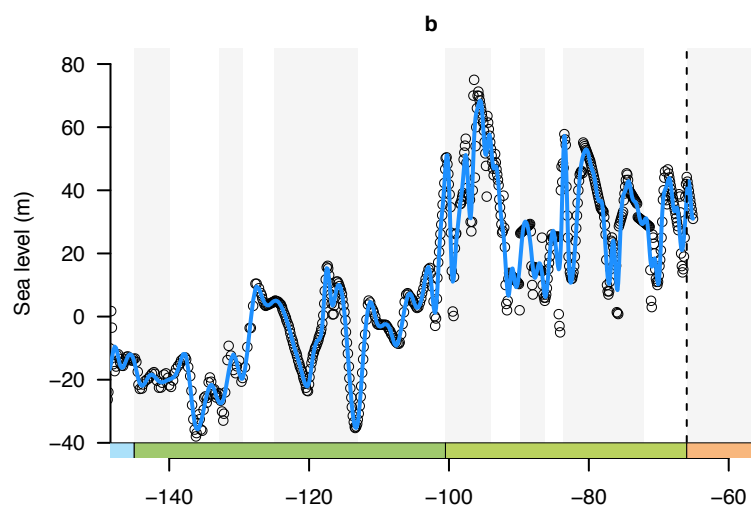
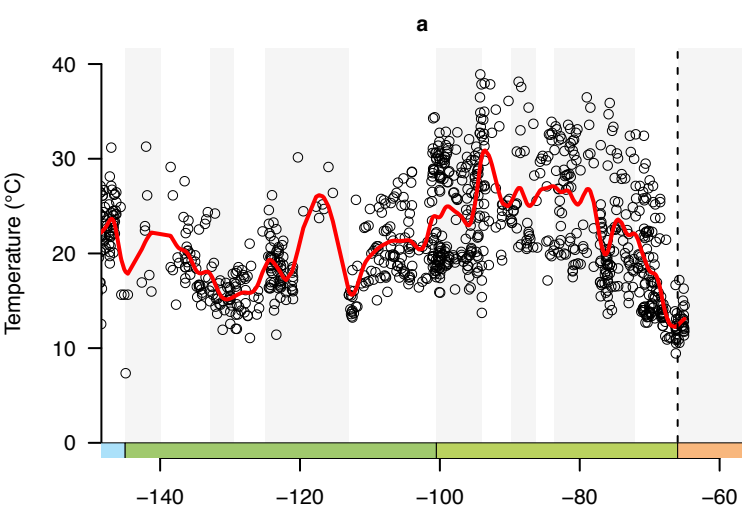
Supplementary Figure 9. Diversification and diversity dynamics of Late Cretaceous troodontids. The Bayesian RJMCMC model estimates speciation rate (**a**), time shifts in speciation rate (**b**), extinction rate (**c**), time shifts in extinction rate (**d**), net diversification rate (**e**, speciation minus extinction) rates, and species longevity in million years (**f**). Solid lines indicate mean posterior rates and shaded areas show 95% CI. As in the BDMCMC model, net diversification remained quite constant through time, although it became negative ~72 Myrs ago (early Maastrichtian) due to a slight decrease of speciation rate. The vertical dashed red line indicates the Cretaceous-Palaeogene mass extinction (66 Myrs ago).



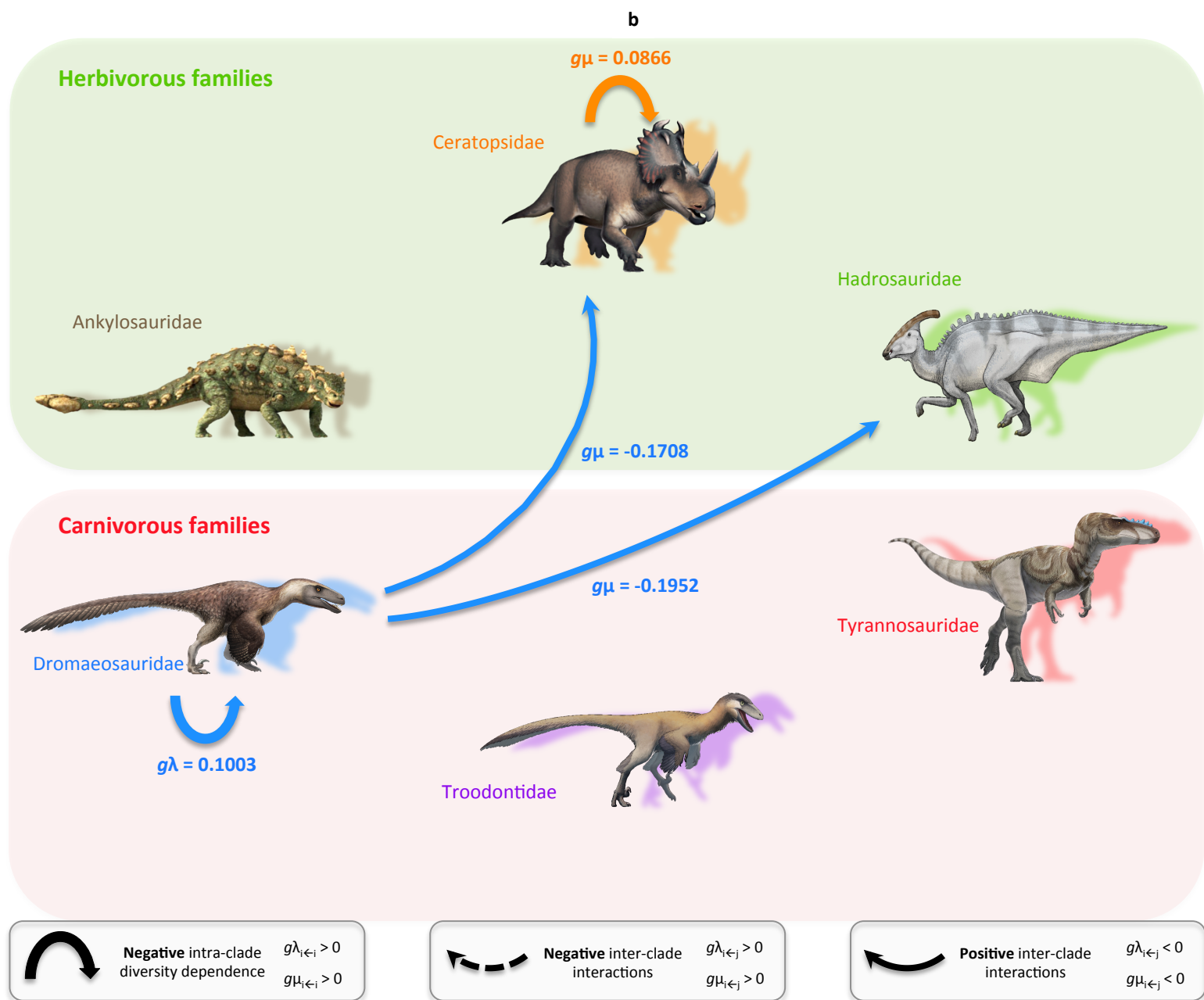
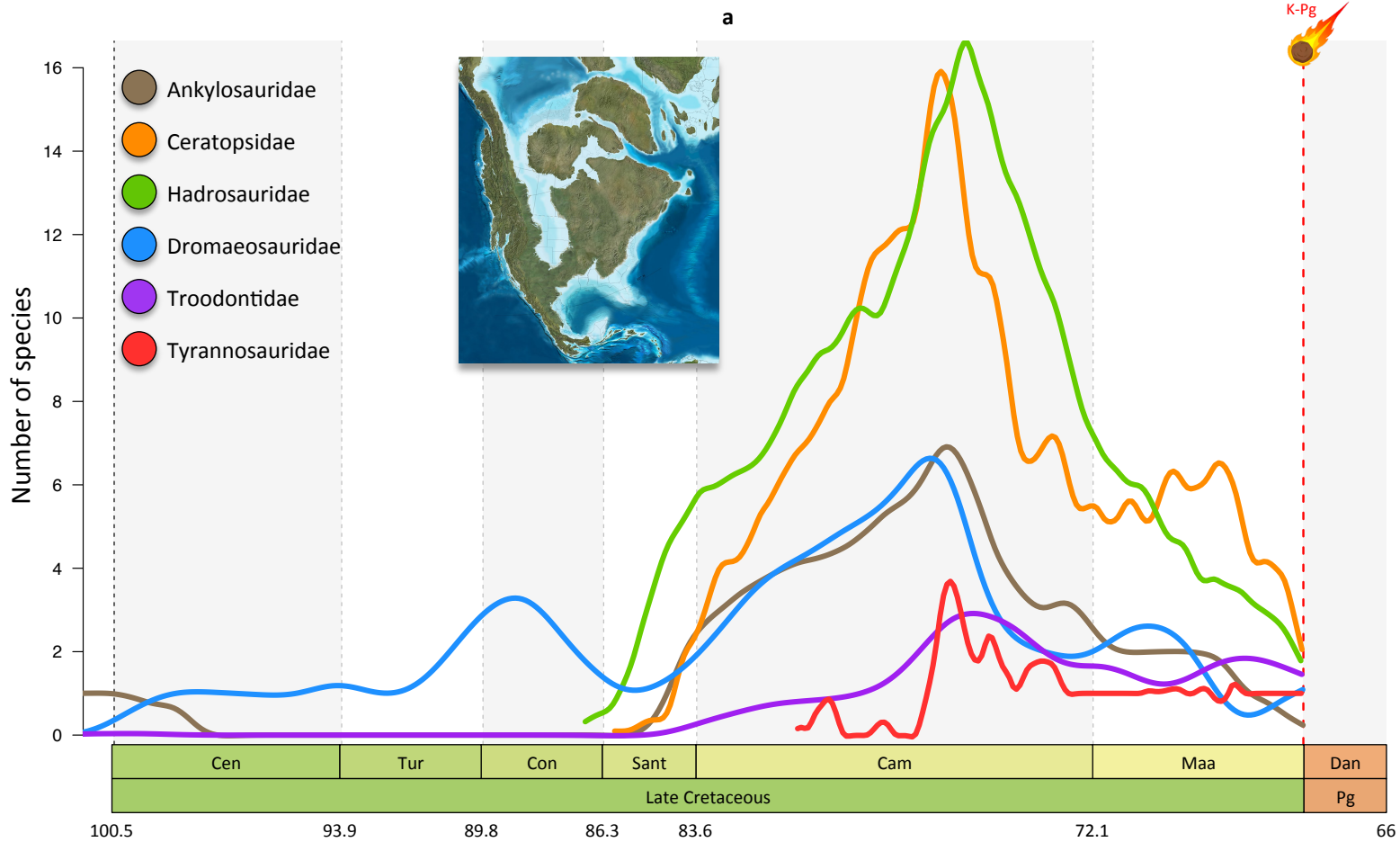
Supplementary Figure 10. Diversification and diversity dynamics of Late Cretaceous tyrannosaurs. The Bayesian RJMCMC model estimates speciation rate (**a**), time shifts in speciation rate (**b**), extinction rate (**c**), time shifts in extinction rate (**d**), net diversification rate (**e**, speciation minus extinction) rates, and species longevity in million years (**f**). Solid lines indicate mean posterior rates and shaded areas show 95% CI. As in the BDMCMC model, net diversification decrease and became negative ~72 Myrs ago (early Maastrichtian) due to a decrease of speciation rate. The vertical dashed red line indicates the Cretaceous-Palaeogene mass extinction (66 Myrs ago).



Supplementary Figure 11. Graphical visualizations of the seven paleo-environmental variables tested as abiotic or biotic drivers of dinosaur diversification. The variations of global deep-sea temperatures (**a**) and the fluctuations of sea level (**b**) are estimated from relative proportions of different oxygen isotopes ($\delta^{18}\text{O}$) in samples of benthic foraminifer shells. The continental fragmentation (**c**) was estimated using paleogeographic reconstructions for 1-million-year time intervals. The relative diversity of angiosperms (**d**), gymnosperms (**e**), non-Polypodiales ferns (**f**), and Polypodiales ferns (**g**) are estimated from analyses of the vascular plant fossil record (see *Methods*). The vertical dashed black line indicates the Cretaceous-Palaeogene mass extinction (66 Myrs ago).



Supplementary Figure 12. Diversity trajectories and the effect of competition on diversification rates of North American dinosaur families. The diversity trajectories of the three carnivorous and three herbivorous dinosaur families are estimated at the North American scale **(a)**. Reconstructions of diversity trajectories are the mean of 10 replicates, incorporating uncertainties around the age of the fossil occurrences. The network **(b)** shows the diversity-dependent effects within and between clades on speciation and extinction rates (only significant correlations are shown, Supplementary Table 3). Each arrow indicates the type of interaction imposed by a given group over another, which quantifies the proportion of rate change (decrease/increase for speciation or extinction) associated with the addition of one species of the competing group. Analyses for the global dinosaurs are presented in Fig. 5 and Supplementary Table 2. Abbreviations: Apt: Aptian, Alb: Albian, Cen: Cenomanian, Tur: Turonian, Con: Coniacian, Sant: Santonian, Cam: Campanian, Maa: Maastrichtian, Dan: Danian, Pg: Paleogene, and K-Pg: Cretaceous-Palaeogene mass extinction (66 Myrs ago). Dinosaur pictures courtesy of Fred Wierum (© Wikimedia Commons), Debivort (© Wikimedia Commons), Jack Mayer Wood (© Wikimedia Commons): <https://creativecommons.org/licenses/by-sa/4.0/>. Palaeomap used with permission © 2020 Colorado Plateau Geosystems Inc. Asteroid icon made by Fabien Condamine.



Supplementary Table 1. Posterior parameter estimates for the MBD model applied to all families. Baseline speciation and extinction rates (λ_0 and μ_0) and correlation parameters ($G\lambda$ and $G\mu$). The environmental drivers are numbered as follows: (0) diversity of all dinosaurs through time, (1) diversity of carnivorous dinosaurs through time, (2) diversity of herbivorous dinosaurs through time, (3) angiosperm diversity through time, (4) gymnosperm diversity through time, (5) non-Polypodiales ferns diversity through time, (6) Polypodiales ferns diversity through time, (7) continental fragmentation through time, (8) sea-level fluctuations through time, and (9) global temperature changes through time. Shrinkage weights (ω), based on local and global shrinkage parameters, and global shrinkage (τ). Shrinkage weights greater than 0.5 (highlighted in bold) indicate significant evidence for correlation (positive or negative depending on the respective $G\lambda$ or $G\mu$ value).

Parameters		Exponential model		Linear model	
		Median	95% HPD	Median	95% HPD
Baseline rates	λ_0	0.46	[0.0104, 1.1167]	0.1782	[0.0194, 0.5703]
	μ_0	0.6727	[0.194, 1.3075]	0.5817	[0.2128, 1.0027]
Correlation parameters to speciation	$G\lambda_0_0$	1.11E-03	[-0.0126, 0.0178]	6.00E-04	[-0.0222, 0.0437]
	$G\lambda_0_1$	0.0162	[-0.0147, 0.0649]	0.0134	[-0.0388, 0.2111]
	$G\lambda_0_2$	3.03E-04	[-0.0165, 0.0199]	3.62E-04	[-0.0388, 0.0438]
	$G\lambda_0_3$	-1.064	[-5.3388, 1.174]	-0.0933	[-4.1822, 2.4822]
	$G\lambda_0_4$	0.2208	[-1.5506, 2.1899]	0.3348	[-1.2438, 24.1626]
	$G\lambda_0_5$	-0.1227	[-4.5713, 5.6763]	0.0625	[-4.9594, 8.3138]
	$G\lambda_0_6$	0.6965	[-2.9456, 8.0272]	0.0932	[-3.4696, 7.672]
	$G\lambda_0_7$	0.5471	[-5.0261, 7.2582]	0.2041	[-7.2036, 23.459]
	$G\lambda_0_8$	-0.0023	[-0.0115, 3.6005E-3]	-0.0004	[-0.0156, 0.011]
	$G\lambda_0_9$	0.0109	[-0.0261, 0.0682]	6.49E-03	[-0.0518, 0.1751]
Correlation parameters to extinction	$G\mu_0_0$	-0.0036	[-0.0584, 0.0391]	-0.0009	[-0.0309, 0.0181]
	$G\mu_0_1$	0.0468	[-0.0097, 0.1215]	0.0218	[-0.0103, 0.0791]
	$G\mu_0_2$	-0.0353	[-0.0862, 0]	-0.0155	[-0.0479, 0]
	$G\mu_0_3$	0.663	[-0.9261, 3.3388]	0.0627	[-1.2755, 2.264]
	$G\mu_0_4$	-0.2726	[-1.914, 0.8805]	-0.0353	[-0.8992, 0.8072]
	$G\mu_0_5$	-0.9501	[-3.9205, 1.0223]	-0.5712	[-2.3039, 0.8612]
	$G\mu_0_6$	0.6882	[-1.4416, 4.2949]	0.3454	[-1.137, 5.5999]
	$G\mu_0_7$	0.054	[-5.5823, 5.8856]	-0.0585	[-6.2575, 3.9169]
	$G\mu_0_8$	-0.0012	[-0.0085, 4.6597E-3]	-0.0012	[-0.0074, 2.0571E-3]
	$G\mu_0_9$	-0.0809	[-0.132, -0.028]	-0.0445	[-0.0944, -0.0039]
Shrinkage weights (speciation)	$\omega\lambda_0_0$	0.186	[2.0382E-9, 0.7599]	0.0721	[3.6138E-10, 0.8931]
	$\omega\lambda_0_1$	0.2076	[7.8624E-10, 0.7742]	0.1368	[4.2534E-8, 0.9427]
	$\omega\lambda_0_2$	0.1689	[9.4718E-11, 0.7107]	0.0646	[1.2187E-11, 0.8968]
	$\omega\lambda_0_3$	0.3051	[4.0713E-10, 0.9253]	0.112	[1.0145E-8, 0.9089]
	$\omega\lambda_0_4$	0.2208	[5.1987E-11, 0.8163]	0.1647	[3.7309E-8, 0.9943]

	$\omega\lambda 0_5$	0.2646	[1.0942E-7, 0.8958]	0.0969	[5.5201E-10, 0.9467]
	$\omega\lambda 0_6$	0.2544	[6.7014E-9, 0.9183]	0.0881	[2.9343E-9, 0.9484]
	$\omega\lambda 0_7$	0.2058	[7.4694E-9, 0.8043]	0.0783	[6.6339E-9, 0.9622]
	$\omega\lambda 0_8$	0.2223	[7.6905E-11, 0.8105]	0.0871	[1.0617E-7, 0.8637]
	$\omega\lambda 0_9$	0.164	[5.7246E-8, 0.7308]	0.0656	[3.369E-9, 0.8867]
Shrinkage weights (extinction)	$\omega\mu 0_0$	0.3354	[4.5112E-8, 0.9423]	0.1186	[2.5856E-9, 0.8525]
	$\omega\mu 0_1$	0.3902	[5.3377E-8, 0.9183]	0.1584	[2.1004E-9, 0.8547]
	$\omega\mu 0_2$	0.5554	[3.5436E-6, 0.9721]	0.2898	[1.3866E-7, 0.9128]
	$\omega\mu 0_3$	0.2604	[2.69E-10, 0.8588]	0.0644	[6.4672E-9, 0.7983]
	$\omega\mu 0_4$	0.2098	[2.2316E-9, 0.797]	0.0489	[1.581E-10, 0.6827]
	$\omega\mu 0_5$	0.2595	[8.2911E-9, 0.8474]	0.1061	[1.0711E-8, 0.7682]
	$\omega\mu 0_6$	0.2434	[6.0399E-8, 0.8569]	0.0999	[2.6247E-8, 0.9036]
	$\omega\mu 0_7$	0.2012	[8.0198E-9, 0.7962]	0.054	[7.9448E-12, 0.8023]
	$\omega\mu 0_8$	0.1837	[8.1776E-9, 0.7439]	0.069	[1.9047E-10, 0.7439]
	$\omega\mu 0_9$	0.5061	[0.0979, 0.978]	0.2713	[1.6412E-5, 0.8765]
Global shrinkage	τ	0.4131	[0.085, 0.9571]	0.3546	[0.0446, 1.1134]
Hyperprior	η	4.0051	[2.4316, 7.0632]	4.1757	[2.1167, 5.8446]

Supplementary Table 2. Posterior parameter estimates for the MCDD model applied to all families. The clades are numbered as follows: (0) Ankylosauridae, (1) Ceratopsidae, (2) Dromaeosauridae, (3) Hadrosauridae, (4) Troodontidae, and (5) Tyrannosauridae. Baseline speciation represents the speciation rate for a clade in absence of diversity dependence. $g\lambda_{0_0}$ denotes for diversity dependence in the clade 0. $g\lambda_{0_1} > 0$ indicates the diversity of clade 1 negatively correlates with speciation of clade 0 (increasing diversity of clade 1 correlates with low speciation of clade 0). $g\lambda_{0_1} < 0$ indicates the diversity of clade 1 positively correlates with speciation of clade 0 (increasing diversity of clade 1 correlates with high speciation of clade 0). Bold values are significant correlations.

Parameters		Exponential model		Linear model	
		Median	95% HPD	Median	95% HPD
Baseline speciation	λ_0	0.2286	[0.0852, 0.4822]	0.2296	[0.0838, 0.4806]
	λ_1	0.3589	[0.0726, 0.7502]	0.3539	[0.0699, 0.7354]
	λ_2	0.4215	[0.2082, 0.6659]	0.4192	[0.2077, 0.6636]
	λ_3	0.3535	[0.1007, 0.6564]	0.3505	[0.0976, 0.6481]
	λ_4	0.5214	[0.2687, 0.8262]	0.52	[0.2673, 0.8258]
	λ_5	0.7639	[0.0835, 2.3089]	0.7454	[0.0785, 2.2976]
Baseline extinction	μ_0	0.1218	[0.0443, 0.2333]	0.1227	[0.0446, 0.235]
	μ_1	0.1925	[0.0475, 0.4971]	0.1956	[0.0506, 0.5041]
	μ_2	0.275	[0.138, 0.4456]	0.2739	[0.1388, 0.4442]
	μ_3	0.2616	[0.0784, 0.4906]	0.2604	[0.0843, 0.4919]
	μ_4	0.4172	[0.208, 0.686]	0.417	[0.2036, 0.675]
	μ_5	0.4181	[0.0646, 1.1572]	0.4179	[0.0667, 1.154]
Intra-family diversity dependence	$g\lambda_{0_0}$	2.76E-03	[-0.0298, 0.2993]	0.0105	[-0.0268, 0.2999]
	$g\mu_{0_0}$	0	[-0.0681, 0.291]	0	[-0.0742, 0.2911]
	$g\lambda_{1_1}$	0.1308	[0, 0.2756]	0.1286	[0, 0.276]
	$g\mu_{1_1}$	0	[-0.1506, 0.1889]	0	[-0.1588, 0.1848]
	$g\lambda_{2_2}$	0.1661	[0, 0.2879]	0.1654	[0, 0.2878]
	$g\mu_{2_2}$	0.1688	[0, 0.292]	0.1695	[0, 0.2915]
	$g\lambda_{3_3}$	0.0714	[0, 0.1073]	0.0712	[0, 0.1075]
	$g\mu_{3_3}$	0	[-0.0071, 0.1956]	0	[-0.0072, 0.1918]
	$g\lambda_{4_4}$	0.1836	[0, 0.2909]	0.1812	[0, 0.2908]
	$g\mu_{4_4}$	0.0905	[0, 0.2944]	0.0899	[0, 0.2949]
	$g\lambda_{5_5}$	0.2342	[0, 0.2991]	0.2322	[0, 0.2991]
	$g\mu_{5_5}$	0	[-0.1456, 0.3]	0	[-0.1504, 0.3]
Competition or positive interaction over ankylosaurid speciation	$g\lambda_{0_1}$	-0.0525	[-0.2029, 3.7289E-3]	-0.0525	[-0.2055, 4.807E-4]
	$g\lambda_{0_2}$	0	[-0.0868, 0.2804]	0	[-0.0949, 0.277]
	$g\lambda_{0_3}$	0	[-0.1006, 0.0428]	0	[-0.0992, 0.0425]
	$g\lambda_{0_4}$	0	[-0.1567, 0.1951]	0	[-0.1526, 0.1967]
	$g\lambda_{0_5}$	0	[-0.2944, 0.1794]	0	[-0.2992, 0.175]

Competition or positive interaction over ankylosaurid extinction	$g\mu 0_1$	0	[-0.3, 0.0569]	0	[-0.3, 0.0577]
	$g\mu 0_2$	0	[-0.0929, 0.2998]	0	[-0.0923, 0.2998]
	$g\mu 0_3$	5.51E-03	[0, 0.2616]	0	[-0.0001, 0.2583]
	$g\mu 0_4$	0	[-0.2125, 0.3]	0	[-0.2065, 0.3]
	$g\mu 0_5$	0	[-0.1286, 0.2999]	0	[-0.1339, 0.3]
Competition or positive interaction over ceratopsid speciation	$g\lambda 1_0$	-0.1185	[-0.2983, 0]	-0.1147	[-0.2984, 0]
	$g\lambda 1_2$	0	[-0.2999, 0.0225]	0	[-0.2998, 0.0212]
	$g\lambda 1_3$	0	[-0.1856, 0.0543]	0	[-0.1924, 0.0447]
	$g\lambda 1_4$	0	[-0.2981, 0.1341]	0	[-0.2985, 0.1303]
	$g\lambda 1_5$	0	[-0.1068, 0.3]	0	[-0.109, 0.3]
Competition or positive interaction over ceratopsid extinction	$g\mu 1_0$	0	[-0.3, 0.0526]	0	[-0.3, 0.0559]
	$g\mu 1_2$	0	[-0.2999, 0.1488]	0	[-0.3, 0.1408]
	$g\mu 1_3$	0.0906	[0, 0.2859]	0.0893	[0, 0.2857]
	$g\mu 1_4$	0.1446	[-0.0061, 0.3]	0.1456	[-0.0113, 0.3]
	$g\mu 1_5$	0	[-0.1577, 0.3]	0	[-0.161, 0.3]
Competition or positive interaction over dromaeosaurid speciation	$g\lambda 2_0$	0	[-0.2237, 0.0171]	0	[-0.2255, 0.0149]
	$g\lambda 2_1$	0	[-0.0452, 0.0811]	0	[-0.0501, 0.0762]
	$g\lambda 2_3$	0	[-0.0706, 2.1077E-3]	0	[-0.0704, 2.1922E-3]
	$g\lambda 2_4$	0	[-0.2878, 2.3976E-4]	-0.0002	[-0.2883, 4.5311E-7]
	$g\lambda 2_5$	0	[-0.296, 0.146]	0	[-0.2987, 0.1392]
Competition or positive interaction over dromaeosaurid extinction	$g\mu 2_0$	-0.1656	[-0.2865, 0]	-0.1668	[-0.2864, 0]
	$g\mu 2_1$	0	[-0.2313, 0.0794]	0	[-0.2299, 0.081]
	$g\mu 2_3$	0	[-0.0131, 0.1249]	0	[-0.0159, 0.1232]
	$g\mu 2_4$	0	[-0.1724, 0.2572]	0	[-0.1636, 0.2631]
	$g\mu 2_5$	3.12E-03	[-0.0645, 0.3]	5.99E-03	[-0.0578, 0.3]
Competition or positive interaction over hadrosaurid speciation	$g\lambda 3_0$	-0.0491	[-0.2807, 0]	-0.0505	[-0.2796, 0]
	$g\lambda 3_1$	0	[-0.0779, 0.1127]	0	[-0.0768, 0.114]
	$g\lambda 3_2$	0	[-0.1857, 0.0674]	0	[-0.1798, 0.078]
	$g\lambda 3_4$	-0.0899	[-0.2554, 6.3557E-4]	-0.0894	[-0.2564, 1.0415E-5]
	$g\lambda 3_5$	0	[-0.264, 0.2035]	0	[-0.2694, 0.1934]
Competition or positive interaction over hadrosaurid extinction	$g\mu 3_0$	0	[-0.1707, 0.1498]	0	[-0.1807, 0.1416]
	$g\mu 3_1$	0	[-0.2257, 0.0139]	0	[-0.2124, 0.0231]
	$g\mu 3_2$	-0.0939	[-0.2879, 0]	-0.0961	[-0.2876, 0]
	$g\mu 3_4$	0	[-0.065, 0.2484]	0	[-0.0551, 0.2624]
	$g\mu 3_5$	0	[-0.2756, 0.0958]	0	[-0.2935, 0.0752]
Competition or positive interaction over troodontid speciation	$g\lambda 4_0$	0	[-0.2681, 0.1077]	0	[-0.2741, 0.1015]
	$g\lambda 4_1$	0	[-0.1474, 0.0768]	0	[-0.1477, 0.0776]
	$g\lambda 4_2$	0	[-0.2805, 0.037]	0	[-0.2797, 0.0359]
	$g\lambda 4_3$	0	[-0.0746, 0.0309]	0	[-0.0707, 0.035]
	$g\lambda 4_5$	0	[-0.2991, 0.1623]	0	[-0.286, 0.179]
Competition or	$g\mu 4_0$	0	[-0.2721, 0.0353]	0	[-0.2724, 0.0419]

positive interaction over troodontid extinction	$g\mu 4_1$	0	[-0.2118, 0.0645]	0	[-0.2235, 0.0625]
	$g\mu 4_2$	0	[-0.0745, 0.2993]	0	[-0.0796, 0.2997]
	$g\mu 4_3$	0	[-0.0348, 0.0703]	0	[-0.0393, 0.0753]
	$g\mu 4_5$	0	[-0.1584, 0.3]	0	[-0.1627, 0.3]
Competition or positive interaction over tyrannosaurid speciation	$g\lambda 5_0$	0	[-0.2998, 6.7882E-3]	0	[-0.2999, 6.2419E-3]
	$g\lambda 5_1$	0	[-0.2988, 2.9988E-3]	0	[-0.2999, 3.8812E-4]
	$g\lambda 5_2$	0	[-0.2997, 0.0999]	0	[-0.3, 0.112]
	$g\lambda 5_3$	0	[-0.0745, 0.0986]	0	[-0.088, 0.0982]
	$g\lambda 5_4$	0	[-0.131, 0.2712]	0	[-0.1249, 0.2805]
Competition or positive interaction over tyrannosaurid extinction	$g\mu 5_0$	0	[-0.0814, 0.2998]	0	[-0.078, 0.3]
	$g\mu 5_1$	0	[-0.0583, 0.3]	0	[-0.0601, 0.3]
	$g\mu 5_2$	0	[-0.2969, 0.189]	0	[-0.2931, 0.196]
	$g\mu 5_3$	0	[-0.0507, 0.2553]	0	[-0.0537, 0.2537]
	$g\mu 5_4$	0	[-0.2998, 0.1611]	0	[-0.2999, 0.158]
Hyperprior	$\eta 0$	0.5427	[0.2067, 0.8811]	0.5438	[0.2008, 0.876]
	$\eta 1$	0.4807	[0.15, 0.813]	0.482	[0.1566, 0.8154]
	$\eta 2$	0.5088	[0.1907, 0.8339]	0.5076	[0.1849, 0.8305]
	$\eta 3$	0.506	[0.181, 0.8213]	0.5052	[0.1818, 0.8215]
	$\eta 4$	0.557	[0.2221, 0.8751]	0.5572	[0.2271, 0.8826]
	$\eta 5$	0.5667	[0.2185, 0.8896]	0.5632	[0.2234, 0.894]

Supplementary Table 3. Posterior parameter estimates for the MCDD model applied to the North American species. The clades are numbered as follows: (0) Ankylosauridae, (1) Ceratopsidae, (2) Dromaeosauridae, (3) Hadrosauridae, (4) Troodontidae, and (5) Tyrannosauridae. Baseline speciation represents the speciation rate for a clade in absence of diversity dependence. $g\lambda0_0$ denotes for diversity dependence in the clade 0. $g\lambda0_1 > 0$ indicates the diversity of clade 1 negatively correlates with speciation of clade 0 (increasing diversity of clade 1 correlates with low speciation of clade 0). $g\lambda0_1 < 0$ indicates the diversity of clade 1 positively correlates with speciation of clade 0 (increasing diversity of clade 1 correlates with high speciation of clade 0). Bold values are significant correlations.

Parameters		Exponential model		Linear model	
		Median	95% HPD	Median	95% HPD
Baseline speciation	$\lambda0$	0.1925	[0.0432, 0.4264]	0.1919	[0.0438, 0.4256]
	$\lambda1$	0.4307	[0.1552, 0.7722]	0.4318	[0.1561, 0.7795]
	$\lambda2$	0.312	[0.141, 0.5283]	0.3122	[0.1403, 0.5284]
	$\lambda3$	0.2248	[0.0818, 0.3916]	0.224	[0.0805, 0.3917]
	$\lambda4$	0.3805	[0.0936, 0.8353]	0.3783	[0.0895, 0.8274]
	$\lambda5$	0.3621	[0.0803, 0.9824]	0.3615	[0.0826, 0.9799]
Baseline extinction	$\mu0$	0.2017	[0.0453, 0.4343]	0.2035	[0.0425, 0.4371]
	$\mu1$	0.3766	[0.1638, 0.63]	0.3745	[0.1641, 0.6274]
	$\mu2$	0.244	[0.1012, 0.4273]	0.2444	[0.1011, 0.4255]
	$\mu3$	0.3105	[0.0878, 0.5649]	0.3103	[0.0862, 0.5619]
	$\mu4$	0.4486	[0.1187, 0.9622]	0.4468	[0.1246, 0.9612]
	$\mu5$	0.3854	[0.0932, 0.9066]	0.3852	[0.1001, 0.9066]
Intra-family diversity dependence	$g\lambda0_0$	0	[-0.0871, 0.3]	0	[-0.0913, 0.3]
	$g\mu0_0$	0	[-0.1747, 0.3]	0	[-0.1772, 0.3]
	$g\lambda1_1$	0.0275	[-0.0006, 0.2444]	0.0289	[-0.0012, 0.2454]
	$g\mu1_1$	0.0866	[0, 0.2884]	0.085	[0, 0.2899]
	$g\lambda2_2$	0.1003	[0, 0.2851]	0.0997	[0, 0.2863]
	$g\mu2_2$	0	[-0.173, 0.2174]	0	[-0.1703, 0.2182]
	$g\lambda3_3$	0	[-0.0627, 0.1475]	0	[-0.0636, 0.1487]
	$g\mu3_3$	0	[-0.0032, 0.2505]	0	[-0.0043, 0.2469]
	$g\lambda4_4$	0.1355	[-0.0455, 0.3]	0.1339	[-0.044, 0.3]
	$g\mu4_4$	0.0815	[-0.0236, 0.3]	0.0808	[-0.0236, 0.3]
	$g\lambda5_5$	0	[-0.1241, 0.3]	0	[-0.1215, 0.3]
	$g\mu5_5$	0	[-0.1666, 0.3]	0	[-0.167, 0.3]
Competition or positive interaction over ankylosaurid speciation	$g\lambda0_1$	0	[-0.2058, 0.1962]	0	[-0.2015, 0.2045]
	$g\lambda0_2$	0	[-0.2999, 0.1546]	0	[-0.3, 0.1493]
	$g\lambda0_3$	0	[-0.2932, 2.2692E-5]	0	[-0.2949, 2.9096E-6]
	$g\lambda0_4$	0	[-0.2268, 0.2993]	0	[-0.2254, 0.2996]
	$g\lambda0_5$	0	[-0.2388, 0.2799]	0	[-0.2463, 0.272]

Competition or positive interaction over ankylosaurid extinction	$g\mu 0_1$	0	[-0.21, 0.2359]	0	[-0.212, 0.2331]
	$g\mu 0_2$	-0.1256	[-0.3, 0.0327]	-0.1272	[-0.3, 0.0326]
	$g\mu 0_3$	0	[-0.04, 0.2749]	0	[-0.029, 0.2885]
	$g\mu 0_4$	2.03E-03	[-0.0948, 0.3]	5.59E-03	[-0.0877, 0.3]
	$g\mu 0_5$	0	[-0.0945, 0.3]	0	[-0.093, 0.3]
Competition or positive interaction over ceratopsid speciation	$g\lambda 1_0$	0	[-0.3, 0.1105]	0	[-0.3, 0.1038]
	$g\lambda 1_2$	0	[-0.2986, 9.7837E-3]	0	[-0.2901, 0.02]
	$g\lambda 1_3$	0	[-0.2003, 0.0441]	0	[-0.2087, 0.0401]
	$g\lambda 1_4$	0	[-0.179, 0.2998]	0	[-0.1816, 0.2971]
	$g\lambda 1_5$	0	[-0.0922, 0.3]	0	[-0.0883, 0.3]
Competition or positive interaction over ceratopsid extinction	$g\mu 1_0$	-0.0673	[-0.3, 0.1025]	-0.0637	[-0.3, 0.1124]
	$g\mu 1_2$	-0.1708	[-0.2981, 0]	-0.1746	[-0.2985, 0]
	$g\mu 1_3$	0	[-0.2371, 0.112]	0	[-0.2333, 0.119]
	$g\mu 1_4$	0.0372	[-0.0929, 0.3]	0.0447	[-0.0968, 0.3]
	$g\mu 1_5$	0	[-0.1378, 0.3]	0	[-0.1359, 0.3]
Competition or positive interaction over dromaeosaurid speciation	$g\lambda 2_0$	0	[-0.2153, 0.2033]	0	[-0.2179, 0.1982]
	$g\lambda 2_1$	0	[-0.1259, 0.073]	0	[-0.1198, 0.0747]
	$g\lambda 2_3$	0	[-0.0938, 0.0808]	0	[-0.0898, 0.0828]
	$g\lambda 2_4$	0	[-0.2999, 0.1827]	0	[-0.3, 0.1811]
	$g\lambda 2_5$	0	[-0.1621, 0.3]	0	[-0.1626, 0.2999]
Competition or positive interaction over dromaeosaurid extinction	$g\mu 2_0$	0	[-0.3, 0.0896]	0	[-0.3, 0.0871]
	$g\mu 2_1$	0	[-0.1747, 0.1483]	0	[-0.175, 0.1503]
	$g\mu 2_3$	0	[-0.1132, 0.15]	0	[-0.1134, 0.1511]
	$g\mu 2_4$	0.1296	[-0.0085, 0.3]	0.1337	[-0.0096, 0.3]
	$g\mu 2_5$	0.0896	[-0.0451, 0.3]	0.0913	[-0.0455, 0.3]
Competition or positive interaction over hadrosaurid speciation	$g\lambda 3_0$	0	[-0.2946, 0.108]	0	[-0.2991, 0.1045]
	$g\lambda 3_1$	0	[-0.1172, 0.1315]	0	[-0.1242, 0.1338]
	$g\lambda 3_2$	0	[-0.2998, 0.0568]	0	[-0.299, 0.0585]
	$g\lambda 3_4$	0	[-0.2445, 0.2458]	0	[-0.2406, 0.2483]
	$g\lambda 3_5$	0	[-0.2372, 0.2358]	0	[-0.2485, 0.2249]
Competition or positive interaction over hadrosaurid extinction	$g\mu 3_0$	0	[-0.3, 0.1165]	0	[-0.3, 0.1161]
	$g\mu 3_1$	0	[-0.173, 0.167]	0	[-0.167, 0.1732]
	$g\mu 3_2$	-0.1952	[-0.2951, 0]	-0.1927	[-0.2952, 0]
	$g\mu 3_4$	0	[-0.1747, 0.3]	0	[-0.1702, 0.3]
	$g\mu 3_5$	0	[-0.239, 0.2431]	0	[-0.2251, 0.255]
Competition or positive interaction over troodontid speciation	$g\lambda 4_0$	0	[-0.3, 0.1265]	0	[-0.2998, 0.1294]
	$g\lambda 4_1$	0	[-0.1715, 0.1501]	0	[-0.173, 0.1487]
	$g\lambda 4_2$	0	[-0.3, 0.0983]	0	[-0.2999, 0.1046]
	$g\lambda 4_3$	0	[-0.1184, 0.1491]	0	[-0.1198, 0.146]
	$g\lambda 4_5$	0	[-0.2573, 0.2587]	0	[-0.2526, 0.2637]
Competition or	$g\mu 4_0$	0	[-0.2998, 0.2317]	0	[-0.2996, 0.2321]

positive interaction over troodontid extinction	$g\mu 4_1$	0	[-0.2999, 0.0228]	0	[-0.3, 0.0185]
	$g\mu 4_2$	0	[-0.3, 0.1432]	0	[-0.3, 0.1412]
	$g\mu 4_3$	0	[-0.0849, 0.1997]	0	[-0.0792, 0.2078]
	$g\mu 4_5$	0	[-0.1866, 0.3]	0	[-0.1869, 0.3]
Competition or positive interaction over tyrannosaurid speciation	$g\lambda 5_0$	0	[-0.3, 0.1118]	0	[-0.3, 0.1115]
	$g\lambda 5_1$	0	[-0.3, 0.0148]	0	[-0.3, 0.0158]
	$g\lambda 5_2$	0	[-0.3, 0.1431]	0	[-0.3, 0.1416]
	$g\lambda 5_3$	0	[-0.2992, 0.0629]	0	[-0.2999, 0.0585]
	$g\lambda 5_4$	0	[-0.2196, 0.3]	0	[-0.218, 0.3]
Competition or positive interaction over tyrannosaurid extinction	$g\mu 5_0$	0	[-0.1509, 0.3]	0	[-0.1544, 0.3]
	$g\mu 5_1$	0	[-0.0733, 0.2999]	0	[-0.0677, 0.3]
	$g\mu 5_2$	0	[-0.194, 0.2999]	0	[-0.19, 0.2999]
	$g\mu 5_3$	0	[-0.0213, 0.2999]	0	[-0.0222, 0.2994]
	$g\mu 5_4$	0	[-0.2784, 0.257]	0	[-0.2828, 0.2532]
Hyperprior	$\eta 0$	0.5004	[0.1674, 0.8383]	0.5001	[0.1594, 0.8333]
	$\eta 1$	0.4865	[0.1557, 0.8188]	0.4848	[0.151, 0.8163]
	$\eta 2$	0.5444	[0.2083, 0.8709]	0.5421	[0.2043, 0.8666]
	$\eta 3$	0.5387	[0.2003, 0.8624]	0.5369	[0.1988, 0.8627]
	$\eta 4$	0.5367	[0.196, 0.8698]	0.5379	[0.1952, 0.8689]
	$\eta 5$	0.5064	[0.1749, 0.8394]	0.5053	[0.1707, 0.8344]

Supplementary Table 4. Posterior parameter estimates for the age-dependent extinction (ADE) model for dinosaurs. Preservation rates (q) are estimated for the Late Cretaceous entirely, the Campanian and Maastrichtian separately, and the pre-decline and decline phases. Bold values for the shape parameter of the Weibull distribution indicate a significant effect of taxon age on extinction rates. A Weibull shape significantly greater than 1 indicates that extinction probability increases with species age, while a Weibull shape significantly lesser than 1 indicates that extinction rate is higher in younger taxa (Weibull shape not significantly different from 1 means no effect of age on extinction rates).

Late Cretaceous					
Parameters	q	alpha	Weibull shape	Weibull scale	Mean longevity (Myrs)
mean	5.6357	0.3234	1.0796	4.4953	4.3916
median	5.5715	0.3165	1.0774	4.483	4.3759
95% HPD	[4.9067, 6.4723]	[0.2776, 0.3984]	[0.8555, 1.2997]	[3.6713, 5.3735]	[3.6667, 5.1015]
Campanian					
Parameters	q	alpha	Weibull shape	Weibull scale	Mean longevity (Myrs)
mean	4.6985	0.3526	0.8505	3.3063	3.654
median	4.6904	0.35	0.8468	3.2808	3.6097
95% HPD	[4.0541, 5.3331]	[0.2952, 0.4164]	[0.6155, 1.104]	[2.0257, 4.5509]	[2.615, 4.7851]
Maastrichtian					
Parameters	q	alpha	Weibull shape	Weibull scale	Mean longevity (Myrs)
mean	8.88E+00	0.3194	1.7572	3.82E+00	3.4295
median	8.8128	0.317	1.7333	3.811	3.4107
95% HPD	[7.7415, 10.2212]	[0.2722, 0.3711]	[1.1362, 2.4768]	[2.9276, 4.7371]	[2.6608, 4.206]
Pre-decline phase					
Parameters	q	alpha	Weibull shape	Weibull scale	Mean longevity (Myrs)
mean	1.522	0.7981	0.7531	1.4061	1.7263
median	1.4084	0.4834	0.7181	1.2822	1.6017
95% HPD	[0.6424, 2.6992]	[0.1105, 2.0321]	[0.3044, 1.2558]	[0.0151, 3.0478]	[0.3551, 3.3521]
Decline phase					
Parameters	q	alpha	Weibull shape	Weibull scale	Mean longevity (Myrs)
mean	8.4253	0.3485	1.488	3.3262	3.026
median	8.4544	0.3478	1.4776	3.3111	3.01
95% HPD	[7.0881, 9.6823]	[0.2946, 0.4036]	[1.0464, 1.9301]	[2.6261, 4.0946]	[2.4248, 3.6549]