Supporting Information for

Larger brain size indirectly increases vulnerability to extinction in mammals.

by A. Gonzalez-Voyer, M. González-Suárez, C. Vilá and E. Revilla

Supplementary Methods

To identify species' traits that have been consistently associated with vulnerability to extinction (defined by the IUCN Red List status) we conducted a literature review in the fall of 2013. We searched for global comparative studies that aimed to identify the key intrinsic factors that influenced vulnerability to extinction in mammals. We selected studies searching for correlates of vulnerability, excluding studies that focused on the role of particular traits (and thus, only tested a very limited subset of species' traits).

We located ten studies published from 2000 to 2013 from which we gathered information on which traits were analyzed and revealed as consistently significant or relevant for vulnerability (Table S1). Relevance was scored as 0 if the trait was tested but not identified as significant or selected in any tested models, 1 if the trait was significant or selected in only some models, or 2 if the trait was significant or selected in all models or the model selected as "best" by the authors. Based on these scores from the 10 studies we then calculated a total trait score (the sum of all scores) to represent overall trait importance.

For our analyses we selected one morphological and one ecological trait. For traits related to reproductive performance we selected those representing the distinct aspects of the slow-fast continuum that had the highest scores and the greatest amount of available data. While the focus was on selected traits from the slow-fast continuum we show results from all traits analysed by the revised studies.

Table S1. Results from 10 global comparative studies of vulnerability to extinction in mammals summarized for each traits as: 0 (trait was evaluated but not identified as relevant), 1 (trait evaluated and identified as relevant in at least one analysis; traits could be identified as relevant for subsets of the data or only in certain combinations of predictors), 2 (trait identified as relevant in all analyses or the model selected as "best" by the authors), and dash (-) to indicate a trait not evaluated in that study. Most studies analyzed mammalian biodiversity in general (with limitations based on available data), except for reference 1 (limited to Carnivora and Primates), reference 2 (Chiroptera), reference 3 (Carnivora), and reference 9 (marine mammals). In addition we report the number of species for which data were available (when analyses were based on different sample sizes we report the largest sample considered to reflect all species that were evaluated) and the total number of evaluated traits (intrinsic traits considered in at least one analysis). The traits selected for this present study are highlighted in bold. The complete reference information is provided below.

Evaluated traits	**References**										**Trait score**	**Times tested**	**Data available**
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]*	[9]	[10]			
Morphological													
Adult body mass	**2**	**1**	**0**	**2**	**2**	**1**	**2**	**2**	**2**	**2**	**16**	**10**	**590**
Neonate body mass	-	-	-	1	-	0	-	-	-	1	2	3	515
Weanling body mass	-	-	-	-	-	-	-	-	2	-	2	1	284

Aspect ratio	-	2	-	-	-	-	-	-	-	-	2	1	0
Adult body length	-	-	-	-	-	-	-	-	-	1	1	1	472
Adult forearm length	-	-	-	-	-	-	-	-	-	1	1	1	33
Teat number	-	-	-	-	-	-	-	-	-	0	0	1	198
Ecological													
Geographic range	2	2	2	2	2	2	2	2	2	2	20	10	592
Pop density	**2**	-	**2**	**2**	**1**	**2**	**2**	**2**	-	**2**	**15**	**8**	**409**
Group size/Sociality	0	1	0	-	-	0	2	-	2	1	6	7	228
Trophic level/Diet	2	-	2	-	-	0	1	-	1	-	6	5	515
Habitat mode	-	-	-	-	1	0	2	-	1	-	4	4	465
Home range	0	-	0	-	-	0	2	-	-	1	3	5	361
Island status	1	1	0	-	-	0	-	-	-	-	2	4	0
Activity period	1	-	0	-	-	0	1	-	-	-	2	4	455
Migratory behavior	-	-	-	-	-	-	-	-	0	-	0	1	0
Reproductive													
Gestation length	**2**	**0**	**2**	**1**	**1**	**1**	-	**2**	-	**1**	**10**	**8**	**564**
Litters year	0	1	-	1	1	1	-	-	2	1	7	7	309
Weaning age	-	-	-	**2**	**1**	**2**	-	**1**	-	**1**	**7**	**5**	**527**
Litter size	**1**	**0**	**0**	-	**1**	**1**	-	-	**0**	**2**	**5**	**7**	**587**
Age sexual maturity	1	0	0	-	1	0	-	-	-	2	4	6	530
Reproductive rate	-	-	-	-	-	-	2	-	0	-	2	2	0
Interbirth interval	0	0	0	-	-	0	-	-	-	1	1	5	408
Age at first breeding	-	-	-	-	-	0	-	-	-	-	0	1	281
Age at eye opening	-	-	-	-	-	0	-	-	-	-	0	1	247
Total evaluated traits	12	7	10	7	25†	17	11	5	11	14	-	-	-
Number of species	355	867	229	4030	1513	4030	4420	5020	125	2761	-	-	-

*This study selected these variables based on previous global comparative studies that indicated these are the most relevant traits for mammals.

†The entire list of tested variables for this study was not provided, the text indicates a database with 25 traits was gathered.

References

1. Purvis, A., et al., *Predicting extinction risk in declining species.* Proceedings of the Royal Society of London B Biological Sciences, 2000. **267**(1456): p. 1947-1952.
2. Jones, K.E., A. Purvis, and J.L. Gittleman, *Biological correlates of extinction risk in bats.* American Naturalist, 2003. **161**(4): p. 601-614.
3. Cardillo, M., et al., *Human population density and extinction risk in the world's carnivores.* PLoS Biology, 2004. **2**(7): p. 909-914.
4. Cardillo, M., et al., *Multiple causes of high extinction risk in large mammal species.* Science, 2005. **309**: p. 1239-1241.
5. Cardillo, M., et al., *Latent extinction risk and the future battlegrounds of mammal conservation.* Proceedings of the National Academy of Sciences of the United States of America, 2006. **103**(11): p. 4157-4161.

6. Cardillo, M., et al., *The predictability of extinction: biological and external correlates of decline in mammals.* Proceedings of the Royal Society B: Biological Sciences, 2008. **275**: p. 1441-1448.
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9. Davidson, A.D., et al., *Drivers and hotspots of extinction risk in marine mammals.* Proceedings of the National Academy of Sciences of the United States of America, 2012. **109**(9): p. 3395-3400.
10. González-Suárez, M. and E. Revilla, *Variability in life-history and ecological traits is a buffer against extinction in mammals.* Ecology Letters, 2013. **16**(2): p. 242-251.

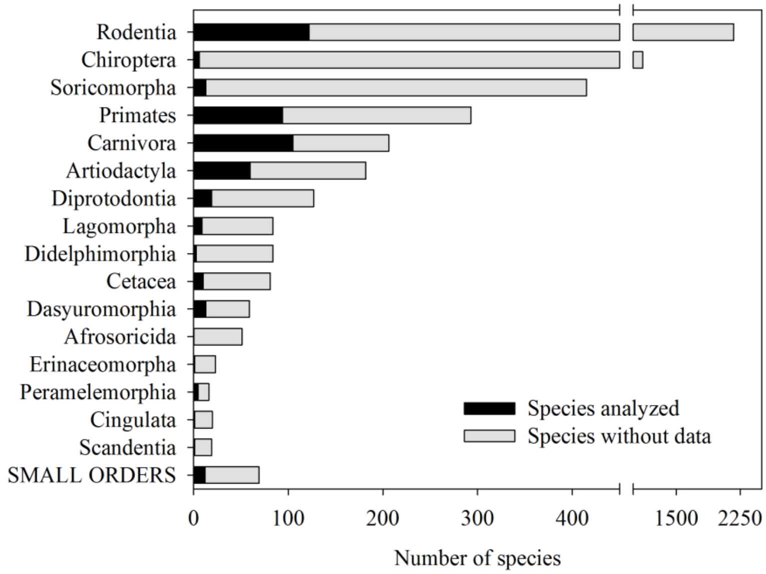

Figure S1. Number of species from each mammalian order for which data was available and hence included in our analyses (in black) in comparison with the known extant diversity of the order (in grey). SMALL ORDERS aggregates data for orders with <20 extant species: Dermoptera, Hyracoidea, Macroscelidea, Microbiotheria, Monotremata, Notoryctemorphia, Paucituberculata, Perissodactyla, Pholidota, Pilosa, Proboscidea, Sirenia, Tubulidentata.

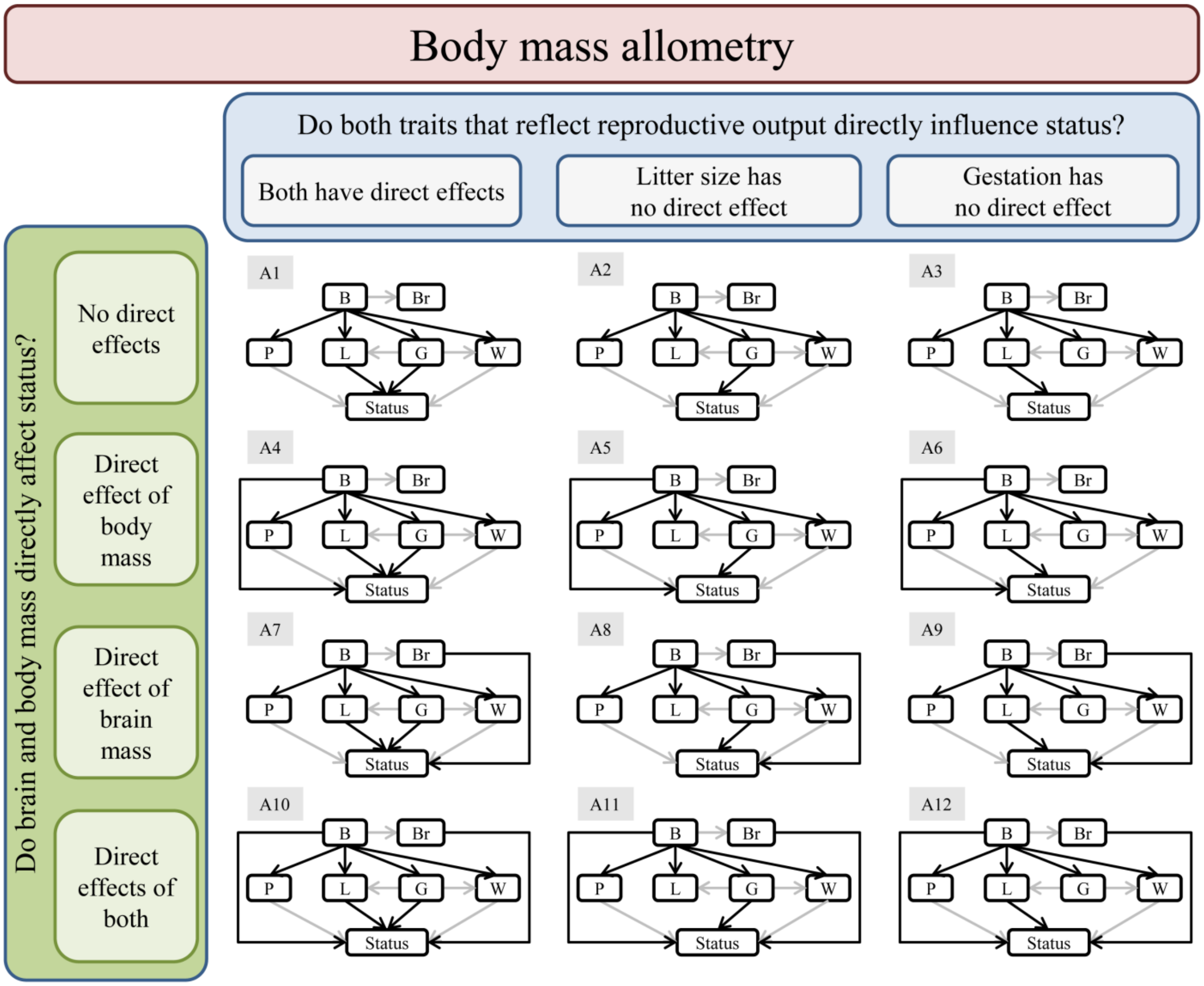

Figure S2. Path models tested under the *Body mass allometry* scenario which reflects the current paradigm in macroecological comparative studies of extinction risk which focus more on the role of body size, rarely considering brain size. Body mass (B), brain mass (Br), litter size (L), gestation length (G), weaning age (W), population density (P), and vulnerability to extinction based on the IUCN Red List categories (Status). Grey arrows indicate known relationships included in all models.

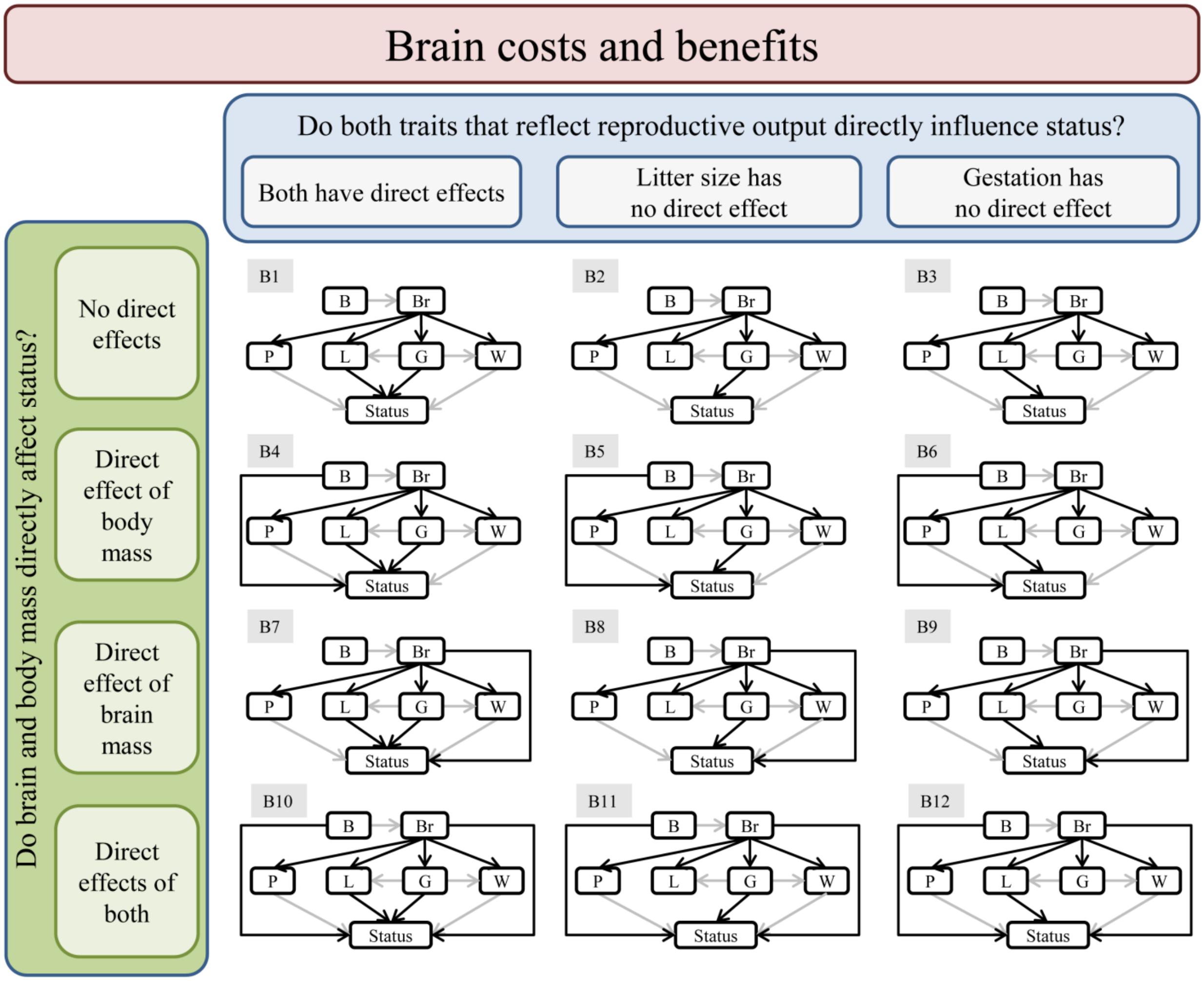

Figure S3. Path models tested under the *Brain costs and benefits* scenario which emphasizes the role of brain size, proposing that previously found correlations between body size and life-history and ecology are best explained by brain size. Body mass (B), brain mass (Br), litter size (L), gestation length (G), weaning age (W), population density (P), and vulnerability to extinction based on the IUCN Red List categories (Status). Grey arrows indicate known relationships included in all models.

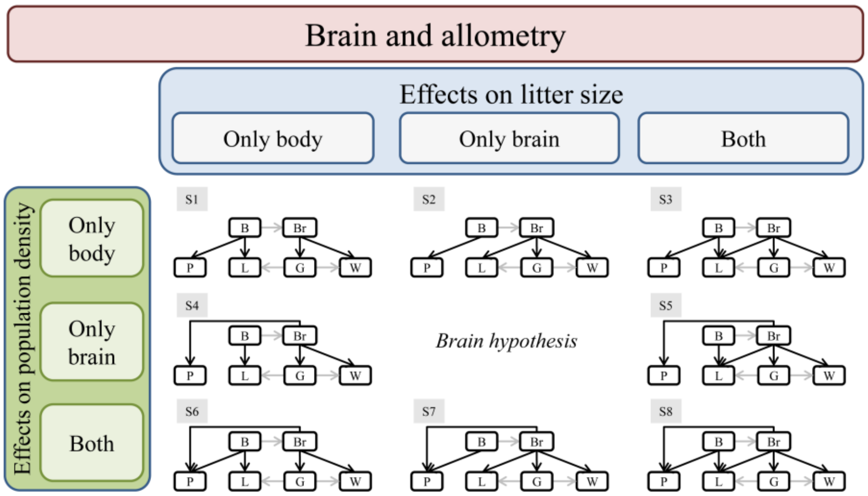

Figure S4. Step 1 of the definition of the path models tested under the *Brain and allometry* scenario. This scenario proposes that both brain and body mass influence life-history and ecological traits. Step 1 was designed to compare different evolutionary relationships between brain and body mass with life-history and population density traits. Body mass (B), brain mass (Br), litter size (L), gestation length (G), weaning age (W), and population density (P). Grey arrows indicate known relationships included in all models.

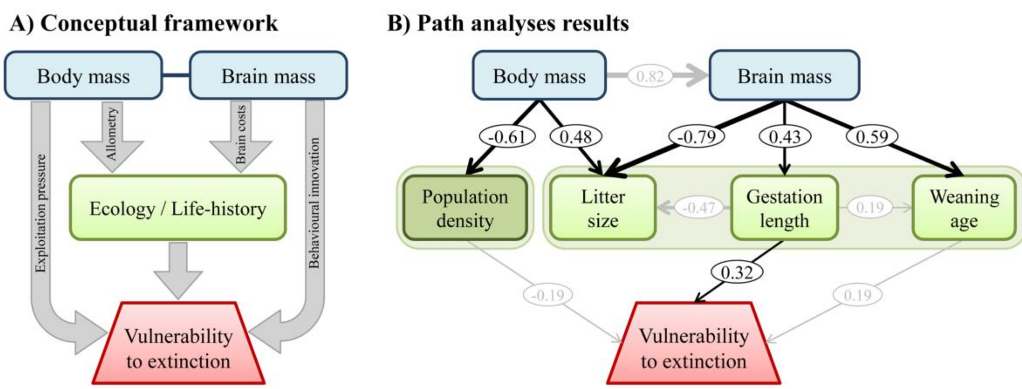

Figure S5. Path diagram results showing the empirical relationships among body mass, brain mass, life history, ecology, and vulnerability to extinction as described by the models best supported by the data (Table S2). These results are based on a dataset that excluded all mammals listed as threatened by the IUCN based on criteria C and/or D (which indicate small population size). The full dataset results are presented in figure 1 of the main text. The width of the arrows indicates their relative importance, and the numbers represent the averaged standardized slope coefficients. Solid arrows represent relationships supported in the model best supported by the data. Grey arrows indicate known relationships included in all models.

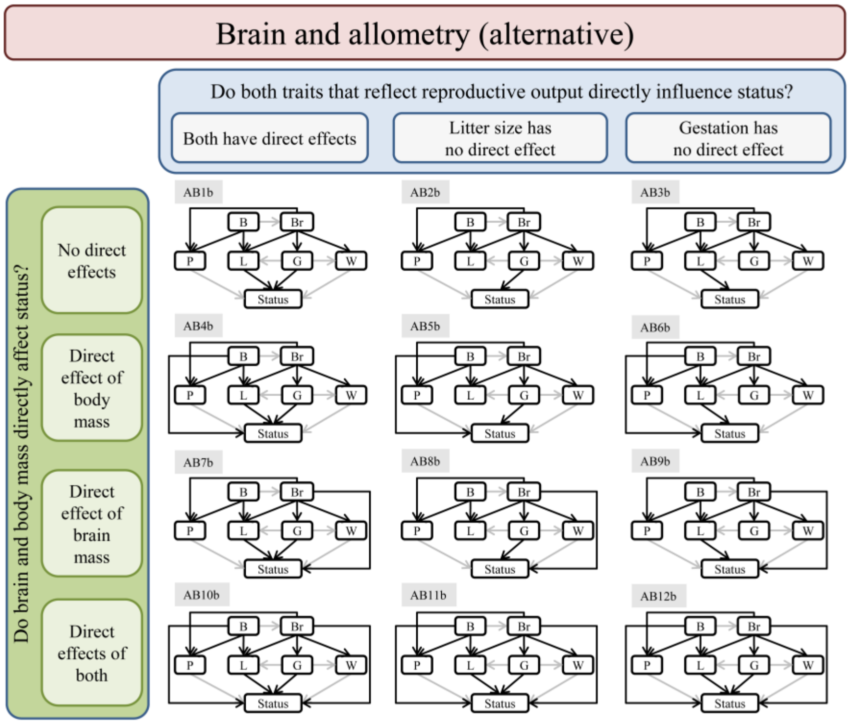

Figure S6. Path models tested under the *Brain and allometry* scenario based on the best supported model from step 1 (Model S8, Fig. S4). This scenario proposes that a combination of allometric effects and energetic costs of brain mass influence life-history and ecological traits. Body mass (B), brain mass (Br), litter size (L), gestation length (G), weaning age (W), population density (P), and vulnerability to extinction based on the IUCN Red List categories (Status). Grey arrows indicate known relationships included in all models.

Table S2. Ranking of all path models tested based on CICc values. Model codes correspond to diagrams presented in figures 2, S2-S3. For each model we report the CICc value, ΔCICc value, CICc weights (ω), C-statistic (C), and *P*-values of the C-statistic, where significant *P*-values indicate the model is rejected by the data. Models were based on 474 mammalian species (Fig. S1). Supported models (ΔCICc <2) are highlighted in bold.

Scenario	**Model**	**CICc**	**ΔCICc**	**ω**	**C**	***P*-value**
Brain and allometry	**AB2**	**57.87**	**0.00**	**0.31**	**20.37**	**0.44**
Brain and allometry	**AB5**	**59.29**	**1.42**	**0.15**	**19.62**	**0.35**
Brain and allometry	**AB8**	**59.56**	**1.69**	**0.13**	**19.89**	**0.34**
Brain and allometry	**AB1**	**59.73**	**1.86**	**0.12**	**20.06**	**0.33**
Brain and allometry	AB11	60.76	2.89	0.07	18.90	0.27
Brain and allometry	AB4	61.15	3.28	0.06	19.30	0.25
Brain and allometry	AB7	61.43	3.55	0.05	19.57	0.24
Brain and allometry	AB3	62.56	4.69	0.03	25.06	0.20
Brain and allometry	AB10	62.69	4.82	0.03	18.65	0.18
Brain and allometry	AB9	64.49	6.62	0.01	24.82	0.13
Brain and allometry	AB6	64.62	6.75	0.01	24.95	0.13
Brain and allometry	AB12	65.46	7.58	0.01	23.60	0.10
Brain	B2	73.19	15.31	0.00	37.84	0.02
Brain	B5	74.48	16.61	0.00	36.98	0.01
Brain	B8	74.59	16.72	0.00	37.09	0.01
Brain	B1	74.92	17.05	0.00	37.42	0.01
Brain	B11	75.94	18.07	0.00	36.27	0.01
Brain	B4	76.33	18.46	0.00	36.66	0.01
Brain	B7	76.61	18.74	0.00	36.93	0.01
Brain	B3	77.76	19.89	0.00	42.42	0.01
Brain	B10	77.86	19.99	0.00	36.01	<0.01
Brain	B9	79.68	21.81	0.00	42.18	<0.01
Brain	B6	79.81	21.94	0.00	42.31	<0.01
Brain	B12	80.64	22.77	0.00	40.96	<0.01
Allometry	A2	115.03	57.16	0.00	79.69	<0.01
Allometry	A5	116.44	58.57	0.00	78.94	<0.01
Allometry	A8	116.62	58.75	0.00	79.12	<0.01
Allometry	A1	116.79	58.92	0.00	79.29	<0.01
Allometry	A11	117.81	59.94	0.00	78.13	<0.01
Allometry	A4	118.20	60.33	0.00	78.53	<0.01
Allometry	A7	118.48	60.60	0.00	78.80	<0.01
Allometry	A3	119.54	61.67	0.00	84.20	<0.01
Allometry	A10	119.73	61.86	0.00	77.88	<0.01
Allometry	A9	121.51	63.64	0.00	84.01	<0.01
Allometry	A6	121.63	63.76	0.00	84.13	<0.01
Allometry	A12	122.51	64.63	0.00	82.83	<0.01

Table S3. Ranking of all path models tested based on CICc values excluding species listed as threatened under criteria C and D by the IUCN (*N*=453). Model codes correspond to diagrams presented in figures 2, S2-S3. For each model we report the CICc value, ΔCICc value, CICc weights (ω), C-statistic (C), and *P*-values of the C-statistic, where significant *P*-values indicate the model is rejected by the data. Supported models (ΔCICc <2) are highlighted in bold.

Scenario	**Model**	**CICc**	**ΔCICc**	**ω**	**C**	***P*-value**
Brain and allometry	**AB2**	**53.46**	**0.00**	**0.32**	**15.88**	**0.72**
Brain and allometry	**AB5**	**54.67**	**1.22**	**0.18**	**14.91**	**0.67**
Brain and allometry	**AB8**	**55.04**	**1.59**	**0.15**	**15.28**	**0.64**
Brain and allometry	AB1	55.51	2.05	0.12	15.75	0.61
Brain and allometry	AB11	56.45	3.00	0.07	14.50	0.56
Brain and allometry	AB4	56.73	3.27	0.06	14.78	0.54
Brain and allometry	AB7	57.10	3.64	0.05	15.15	0.51
Brain and allometry	AB10	58.55	5.09	0.03	14.40	0.42
Brain and allometry	AB6	61.08	7.62	0.01	21.32	0.26
Brain and allometry	AB9	61.38	7.92	0.01	21.62	0.25
Brain and allometry	AB3	62.42	8.97	0.00	24.84	0.21
Brain and allometry	AB12	62.96	9.51	0.00	21.01	0.18
Brain	B2	66.78	13.33	0.00	31.37	0.09
Brain	B5	67.90	14.44	0.00	30.32	0.06
Brain	B8	67.99	14.53	0.00	30.41	0.06
Brain	B1	68.73	15.28	0.00	31.15	0.05
Brain	B11	69.67	16.21	0.00	29.91	0.04
Brain	B4	69.94	16.49	0.00	30.18	0.04
Brain	B7	70.31	16.86	0.00	30.55	0.03
Brain	B10	71.75	18.29	0.00	29.80	0.02
Brain	B6	74.30	20.85	0.00	36.73	0.01
Brain	B9	74.60	21.14	0.00	37.02	0.01
Brain	B3	75.66	22.20	0.00	40.25	0.01
Brain	B12	76.18	22.72	0.00	36.42	0.01
Allometry	A2	110.55	57.10	0.00	75.14	<0.01
Allometry	A5	111.76	58.30	0.00	74.18	<0.01
Allometry	A8	112.06	58.61	0.00	74.48	<0.01
Allometry	A1	112.53	59.08	0.00	74.95	<0.01
Allometry	A11	113.46	60.01	0.00	73.70	<0.01
Allometry	A4	113.74	60.28	0.00	73.98	<0.01
Allometry	A7	114.11	60.65	0.00	74.35	<0.01
Allometry	A10	115.55	62.09	0.00	73.60	<0.01
Allometry	A6	118.07	64.62	0.00	80.49	<0.01
Allometry	A9	118.43	64.98	0.00	80.85	<0.01
Allometry	A3	119.47	66.01	0.00	84.06	<0.01
Allometry	A12	119.97	66.52	0.00	80.21	<0.01

Table S4. Ranking based on CICc values of the path models exploring evolutionary relationships in step 1 of the *Brain and allometry* scenario analysis.
Models S8 and S3 were selected as best supported by the data, because S8 is a version of S3 with an additional path we selected the simplest model (S3) as the basis to construct models in step 2 (Fig. 2 main text). We also explored an alternative set of models for step 2 using S8 (Fig. S6). Results were qualitatively the same (Table S5). Model codes correspond to diagrams presented in figure S4 (step 1). For each model we report the CICc value, ΔCICc value, CICc weights (ω), C-statistic (C), and *P*-values of the C-statistic, where significant *P*-values indicate the model is rejected by the data. Supported models (ΔCICc <2) are highlighted in bold.

Models	CICc	ΔCICc	ω	C	*P*-value
S8	**45.87**	**0.00**	**0.67**	**14.82**	**0.25**
S3	**47.56**	**1.70**	**0.29**	**18.65**	**0.18**
S5	51.62	5.76	0.04	22.71	0.07
S7	56.36	10.50	0.00	27.45	0.02
S2	58.07	12.20	0.00	31.28	0.01
S6	63.54	17.68	0.00	34.63	<0.01
S1	65.25	19.38	0.00	38.46	<0.01
S4	69.31	23.44	0.00	42.52	<0.01

Table S5. Complete models for the *Brain and allometry* scenario based on the alternative best model from step 1 (Table S4). Model codes correspond to path models presented figure S6. For each model we report the CICc value, ΔCICc value, CICc weights (ω), C-statistic (C), and *P*-values of the C-statistic, where significant *P*-values indicate the model is rejected by the data. Supported models (ΔCICc <2) are highlighted in bold.

Models	CICc	ΔCICc	ω	C	*P*-value
AB2b	**56.21**	**0.00**	**0.31**	**16.54**	**0.55**
AB5b	**57.64**	**1.43**	**0.15**	**15.79**	**0.47**
AB8b	**57.91**	**1.70**	**0.13**	**16.06**	**0.45**
AB1b	**58.08**	**1.87**	**0.12**	**16.23**	**0.44**
AB11b	59.12	2.91	0.07	15.08	0.37
AB4b	59.51	3.30	0.06	15.47	0.35
AB7b	59.79	3.57	0.05	15.74	0.33
AB3b	60.90	4.69	0.03	21.23	0.38
AB10b	61.06	4.85	0.03	14.82	0.10
AB9b	62.84	6.63	0.01	20.99	0.18
AB6b	62.97	6.76	0.01	21.12	0.17
AB12b	63.82	7.60	0.01	19.77	0.14

Supplementary Results: *Taxon-specific analyses*

There were minor differences within each order for the relationships between brain, body sizes and life history traits or among life history traits. We therefore had to modify slightly the causal links between traits to ensure that all conditional independencies were met in all models (Fig. S7).

As illustrated in figure S7 the differences in the tested models for the different orders are as follows. For Carnivora and Primates population density is not independent of brain size even when controlling for body size, it is however independent of body size when controlling for brain size. Thus, the causal link was modified to go from brain size to population density. For Primates, weaning age was not independent of litter size, thus a causal link was added from litter size to weaning age. The causal link between litter size and weaning age could be due to the fact that litter size is a proxy for neonate size, which influences weaning age. Alternatively, it may also be a result of the limited variability in litter in Primates. Finally, for Artiodactyla, weaning age depends of body size rather than brain size. Thus, the causal link was modified to go from body size to weaning age.

Note that because of the differences in causal links for the different orders, the models are not directly comparable, because the causal links involved are different.

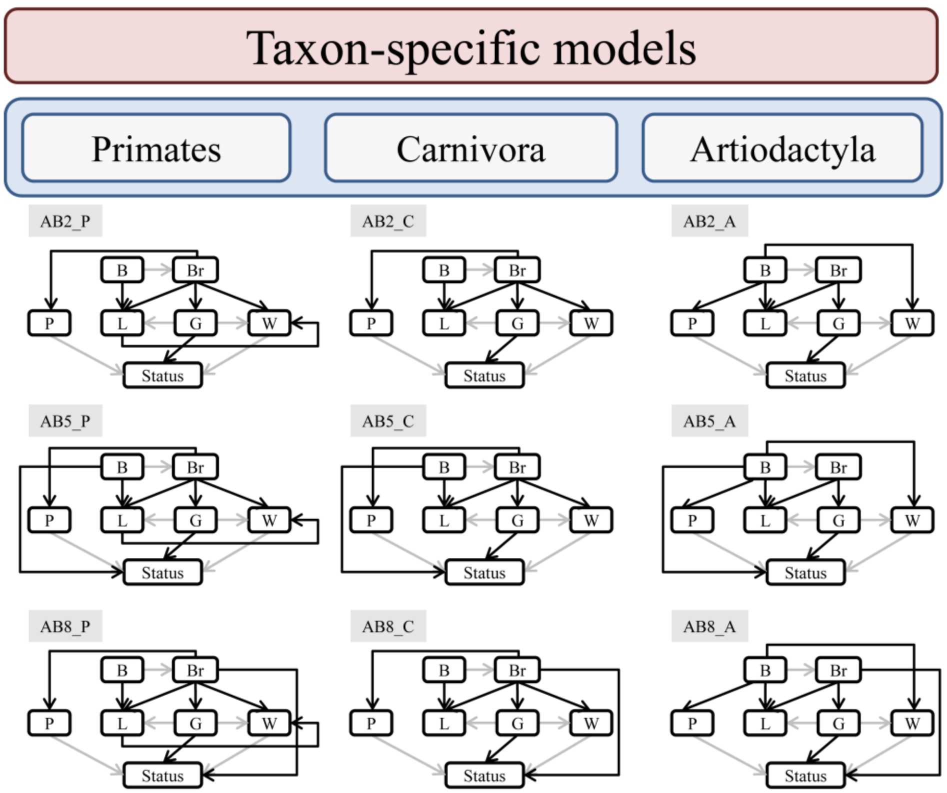

Figure S7. Path models for the three orders for which taxon-specific analyses were possible. Tested model included slight modifications of the three models supported in the overall analyses (AB2, AB5 and AB8, fig 2 main text). Body mass (B), brain mass (Br), litter size (L), gestation length (G), weaning age (W), population density (P), and vulnerability to extinction based on the IUCN Red List categories (Status). Grey arrows indicate known relationships included in all models.

Table S6. Ranking of the three best-supported models based on CICc values for the three orders for which taxon-specific analyses were possible. The table shows the model number only for comparison with the results of the complete database, although as mentioned above the models vary slightly between orders and when compared to those of the complete dataset. For each model we report the CICc value, and C-statistic (C). All C statistic values were non-significant, indicating that minimum set of conditional independencies were fulfilled by the observational data.

Model	**CICc**	**C**	***P*-value**
Primates			
AB2_P	63.02	16.08	0.59
AB5_P	60.12	10.12	0.86
AB8_P	58.58	8.58	0.93
Carnivora			
AB2_C	68.40	24.44	0.22
AB5_C	69.62	22.68	0.20
AB8_C	68.34	21.40	0.26
Artiodactyla			
AB2_A	65.82	13.14	0.87
AB5_A	69.18	12.18	0.84
AB8_A	69.55	12.55	0.82