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Supplementary Materials for

Global wildlife trade across the tree of life

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Materials and Methods

Wildlife trade data

We compiled information on traded birds, mammals, amphibians, and squamate reptiles using two of the most comprehensive data sources on wildlife trade and threat: the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and the International Union for Conservation of Nature Red list of Threatened Species (IUCN Red list). CITES is an international agreement between governments that monitors, restricts and bans international trade in wild animals and plants. CITES lists of traded species were downloaded 1st of January 2017 from (34). A third organization, TRAFFIC, plays an active role in monitoring the global trade of wildlife. However, TRAFFIC does not have a comprehensive list of traded species nor does it have an online platform from which we can autonomously collate data (see below). TRAFFIC does, however, work closely with CITES to inform their listing of species in CITES Appendices. Therefore, TRAFFIC information on traded species should be captured (intrinsically) by our analysis of CITES appendices (below). CITES lists species in three appendices according to the levels or types of protection they need. We included species listed in any of the three CITES Appendices. We identified species traded from the IUCN threat classification scheme as those under the category hunting & collecting terrestrial animals, and subcategory intentional use. This includes hunting and the collection of terrestrial animals (including those living within terrestrial/aquatic boundary). The IUCN threat classification scheme was accessed on the 21st of February 2019, through the IUCN API platform using the R (36) package rredlist (37). We further derived a list of key search words that characterize trade (Table S9), and used an autonomous search algorithm to identify species with keywords in their assessment. To confirm that keywords were indeed related to a description of trade, we carefully read the IUCN Red List assessment for all species detected by our search algorithm. The reliability of CITES and IUCN data quality might be phylogenetically and spatially explicit, but this uncertainty is inherent of any study conducted at this scale.

Given the extensive list of purposes wildlife species are traded for (38), we classified species based on whether they are traded dead or alive. Species traded as dead products are often used for commercial bushmeat, trophy hunting, clothing, medicine, or religion. In contrast, species traded alive are those commercialized as pets, for expositions, circus, or zoological gardens. For simplicity, we refer to species traded dead as products, and traded alive as pets.

Spatial analyses

We superimposed IUCN range maps of bird, mammal, and amphibian species in a 110 x 110 km global grid under a cylindrical equal-area projection, and recorded species presence/absence within each grid cell. Range maps from reptiles were obtained from the recently available assessment provided by Roll et al. (39) and interpolated using the same resolution as for the other vertebrate groups. A species was considered as present in a grid cell if its distribution range fell within the cell boundaries. Coastal cells with < 30% land cover and species considered extinct were excluded from our analysis. We determined wildlife trade richness as the number of traded species within each grid cell. Likewise, pet-trade richness and product-trade richness was determined as the number of species traded as pets or products within a grid cell, respectively. We further assembled species occurring in each of the world's biomes (40) and biogeographical realms (41), and calculated their trade richness, pet-trade richness, and product-trade richness in order to compare trade differences across biologically meaningful regions.

We defined hotpots as the upper 25% and upper 5% richest cells for traded species. We assessed the correlation between spatial patterns in total species richness, traded species richness, and threatened species richness using Pearson's correlation coefficient. We calculated the Clifford's modified t-test to obtain unbiased degrees of freedom of correlation coefficients, while controlling for spatial autocorrelation. Modified t-tests were calculated using the R package SpatialPack (42). We inspected for geographic differences in trade type (products versus pets) by plotting the number of species traded by products against the total number of species traded as pets for each cell. Points falling above a slope of 1 indicate areas where more species traded as products than pets.

Phylogenetic analyses

We used the most comprehensive time-calibrated species-level phylogenetic trees available for each vertebrate group. For birds, we used a phylogenetic tree from Jetz et al. (43), containing 9,993 species of birds, and overlaid on the Hackett family-level backbone, which is the most recent avian topology available. For mammals, we used a phylogenetic tree from Kuhn et al. (44), which builds upon a prior phylogeny from Bininda-Emonds et al. (45) and Fritz et al. (46), and contains 5,020 species. For amphibians, we used a phylogenetic tree from Jetz and Pyron (47), containing nearly all extant amphibian diversity (7,239 species). For reptiles, we used fully sampled phylogenies containing 9,574 squamate (amphisbaenas, lizards, and snakes) species from Tonini et al. (48). We did not include testudine (turtle), crocodylia (crocodiles) and Rhynchocephalia (tutaras) due to limited phylogenetic data. These groups represent less than 5% of the total reptile diversity. Each one of these supertrees are available online as sets of 10,000 trees. From each set of 10,000 trees, we obtained one maximum clade credibility (MCC) tree, and used these MCC trees in downstream analyses. MCC were obtained using the maxCladeCred function from the R package phangorn (49) version 2.4.

We tested for phylogenetic signal in wildlife trade (i.e., whether closely related species are more traded than random) using the D-statistic (16), which was explicitly developed for testing phylogenetic signal in discrete (binary) traits. The D-statistic is the sum of state changes along the edges of a phylogeny. Few state changes indicate that a trait is phylogenetically conserved, whereas numerous state changes indicate that a trait is labile (16). To test the significance of observed phylogenetic signal, we contrasted observed D-values against simulated D-values based on a random and a Brownian motion mode of evolution (16). D-statistics and null models were estimated using the phylo.d function in the R package caper (50).

We assessed the correlation between trade and traits using two methods. First, we used phylogenetic ANOVA (51) to test whether traded species possess traits that are different to the ones of non-traded species. Second, we used phylogenetic logistic regression (52) to test whether traits influence the probability of a species being traded. We used body size and evolutionary distinctiveness as traits. Body size is a widely used proxy for many species ecological and life history traits. Evolutionary distinctiveness measures the evolutionary isolation of lineages (19, 53), thus evolutionarily distinct species may express nonrandom phenotypes (19). Body size data for amphibians were extracted from AmphiBIO as snout-to-vent length (millimeter) because body mass was only available for a few species (54) and for reptiles we used Slavenko's et al. (55) data on body mass (grams). We used the R package missForest (56) to impute missing information in amphibian body size including foraging strategy, offspring per year, breeding strategy, and phylogenetic eigenvectors (57) as predictor variables. For reptiles, we used only body size and phylogenetic eigenvectors as these were the traits available. Phylogenetic eigenvectors were calculated using the R package PVR (58). Body size data for birds and mammals were extracted from Elton traits (59), containing body mass (grams) with interpolated missing values based on taxonomy. We calculated evolutionary distinctiveness using the fair proportion metric proposed by Isaac et al. (53), in the R package picante (60).

To anticipate the risk of currently not traded species becoming threatened by trade in the future, we identified relative probabilities/risk of future trade based on 1) phylogeny and 2) species traits. Here, we used two approaches: First, we identified for each non-traded species the proportion of all species traded in their respective family (a high proportion of related species that are traded equates to a high future risk of trade). Second, for each non-traded species we averaged its phylogenetic distance with the ten closest related species that are traded (a high phylogenetic relatedness with species that are traded equates to a high future risk of trade). We normalized the phylogenetic distances between 0 and 1 thus reflective of the probability of being traded in the future. For traits, we applied a phylogenetic logistic regression to predict the probability of a species becoming traded based on their body size, as well as their evolutionary distinctiveness, while controlling the effect of phylogeny dependency.

<u>Traded Species List</u>

We formed our list of traded terrestrial vertebrates (birds, mammals, amphibians, and squamate reptiles) by using a keyword search, based on 65 terms (see Table S9), of all text listed under each species IUCN assessment. This search included all content from each species assessment but it mainly applied to the following sections: Assessment information, Population, Use and Trade (if present), Threats, and Conservation Actions.

First, we performed a set of pilot searches in order to refine our keyword list. At each round of pilot searches, we selected 200 species from each taxonomic group at random (total of 800 species), and read through the assessment of each species containing a keyword. We refined our keyword list at each round of pilot searches by removing commonly erroneous keywords (e.g. bone, teeth, horn, all of which often relate to description of species morphologies but not necessary animal parts traded) and/or by adding new keywords that were commonly observed on the species' assessments to describe trade. To maximize our balance of search effort and data collection, we included filters to remove species containing certain keywords or phrases that describe species that are not traded. For example, many species contain the section “use and trade” on their IUCN assessment without actually being traded. We therefore removed species when this was the only term returned. Moreover, many species contain the phrase "this species is not known to be traded", and those were also filtered out. After 10 refinements (pilot searches), our keyword algorithm reached accuracy of 85% of species correctly identified as traded. In order to guarantee the accuracy of our keyword search, and determine if a species is traded, we read each IUCN assessment of all species flagged with a keyword as traded to ensure that keywords accurately indicate animal trade. This mining process allowed us to identify an extra 829 species (184 birds, 215 mammals, 132 amphibians, 298 reptiles) that are not listed by CITES nor IUCN under the category hunting & collecting terrestrial animals, and subcategory intentional use.

Supplementary figures

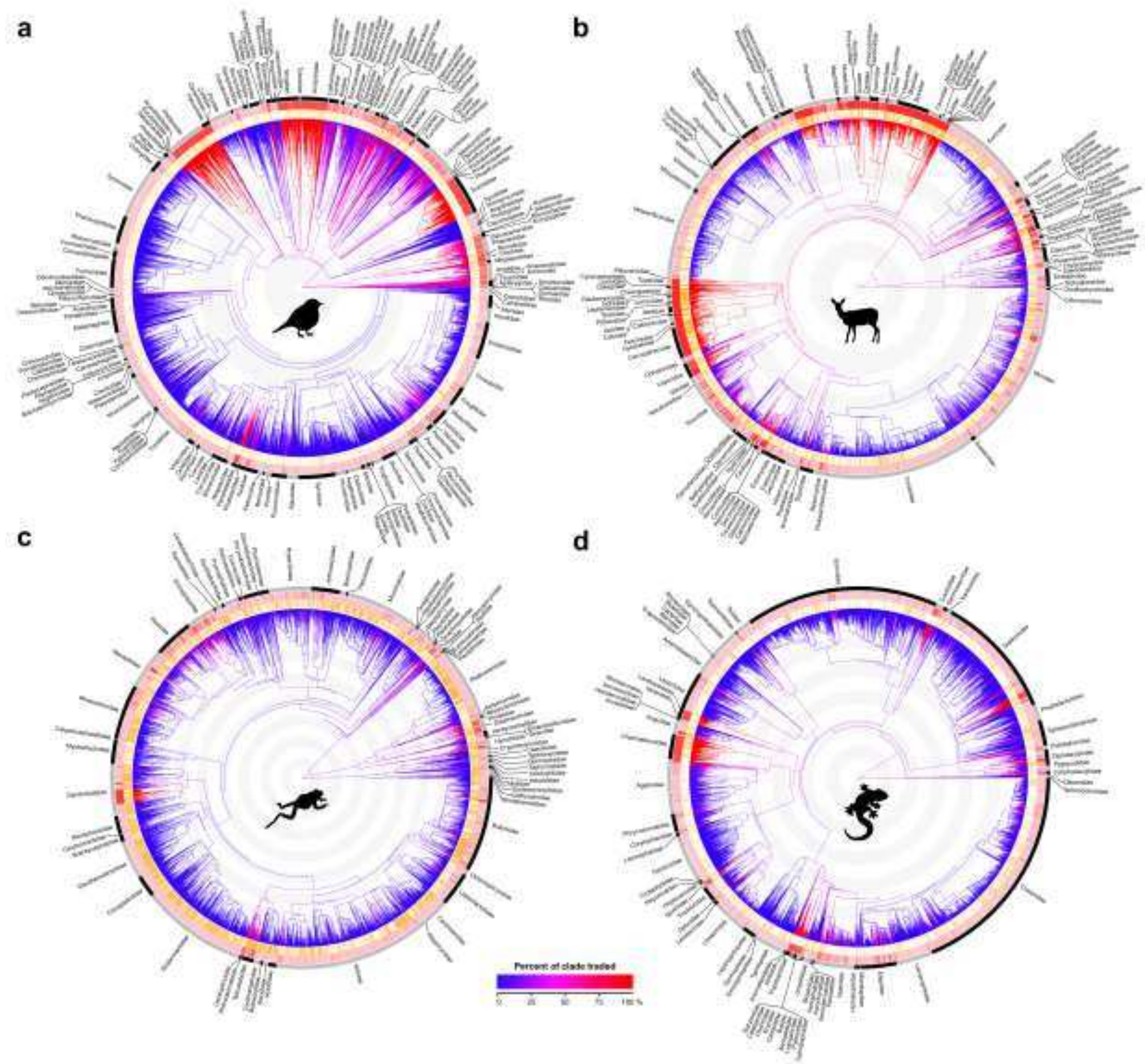

Fig. S1. Wildlife trade occurs across the tree of life, but some clades are more heavily targeted than others. Phylogeny branches for birds (a), mammals (b), amphibians (c) and reptiles (d) are colored to represent the impact of wildlife trade up-to each node (i.e., clade). Warmer colors (red) represent heavily traded branches (i.e., high percent of traded species). All families are labelled. The first outer band indicates threatened (VU, EN, and CR; orange) and non-threatened species (LC and NT; yellow). The second outer band indicates traded (red) and non-traded (pink) species. Gray concentric circles scale a 20 million year period.

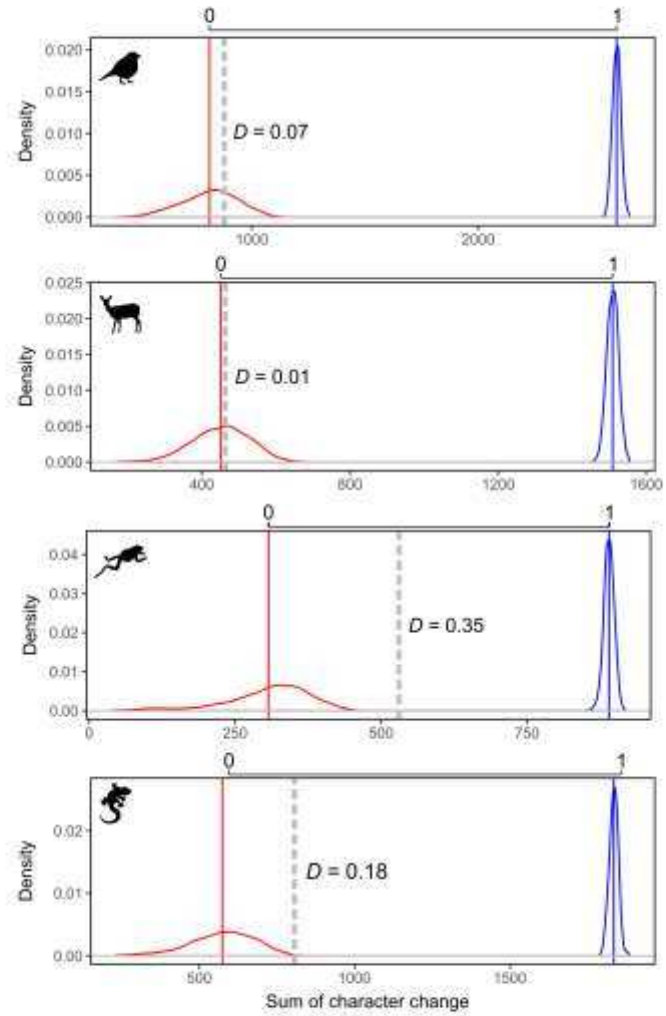

Fig. S2. Phylogenetic signal in wildlife trade for amphibians, birds, mammals and reptiles. Mammals and birds show a signal as strong as expected under a Brownian motion model of evolution indicating high levels of phylogenetic clustering. The D-statistic is the sum of state changes along the edges of a phylogeny. Continuous vertical lines represent the mean of random D-statistic values obtained from two null models: Brownian motion (red) and phylogenetic randomness (blue). Dashed gray lines represent observed D-statistics.

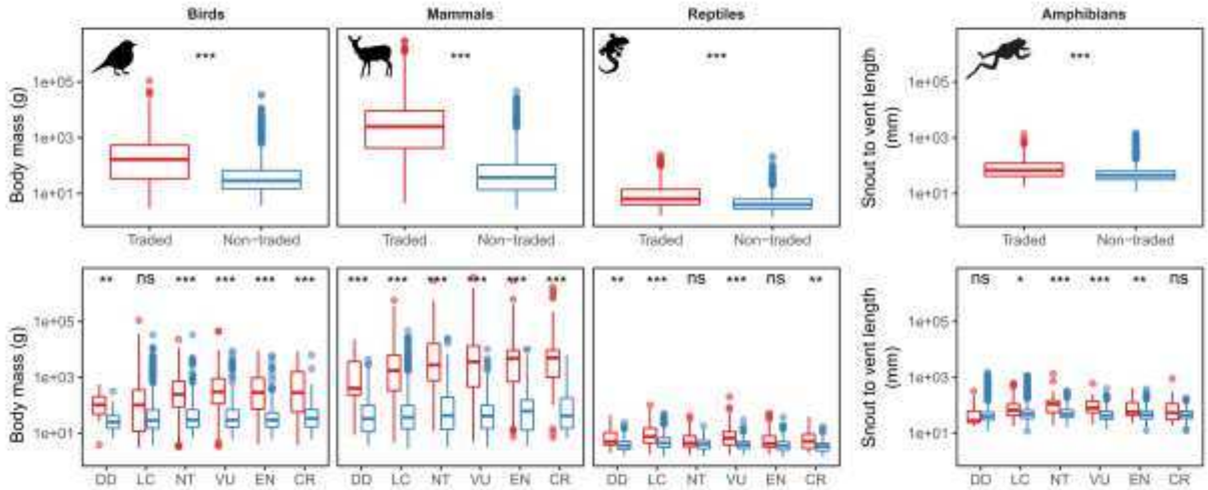

Fig. S3. Variation in body size across traded species. Large-bodied species are more traded than small-bodied species. This pattern emerges regardless of the category of threat (exept for reptiles). Body size in amphibians is represented by snout-to-vent length (millimeters), whereas in birds, mammals and reptiles body size is represented by body mass (grams). Statistics were assessed using the simulation-based phylogenetic ANOVA of Garland et al. (51). * indicates p-value of less than 0.05, ** indicates p-value of less than 0.01, *** indicates p-value of less than 0.001, and ns indicates statistical non-significance. The y-axis is log transformed. Threat status is defined according to the International Union for Conservation of Nature Red list of Threatened Species. DD=Data Deficient; LC=Least Concern; NT=Near Threatened; VU=Vulnerable; EN=Endangered; CR=Critically Endangered.

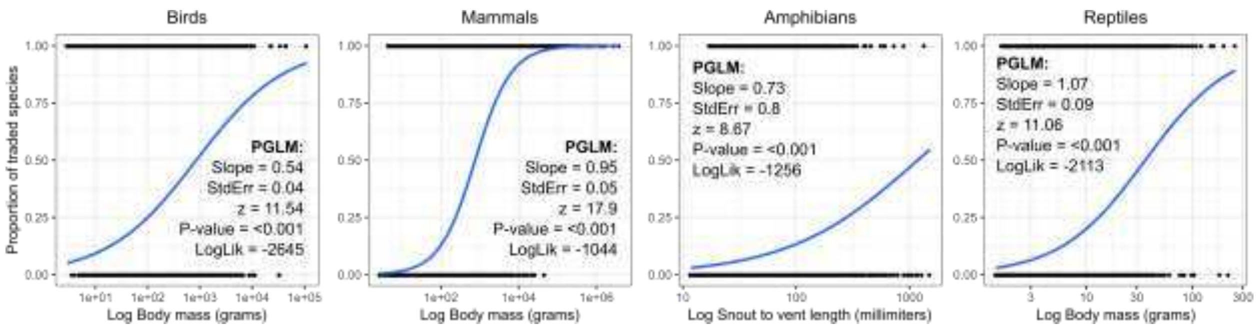

Fig. S4. Relationships between body size and the probability of being traded. Large bodied species have a higher probability of being traded. Significance in relationships were assessed based on the phylogenetic logistic regression method described by Ives and Garland (52). Body size in birds, mammals and reptiles is represented by mass (grams), whereas amphibians are represented by snout-to-vent length (millimeters).

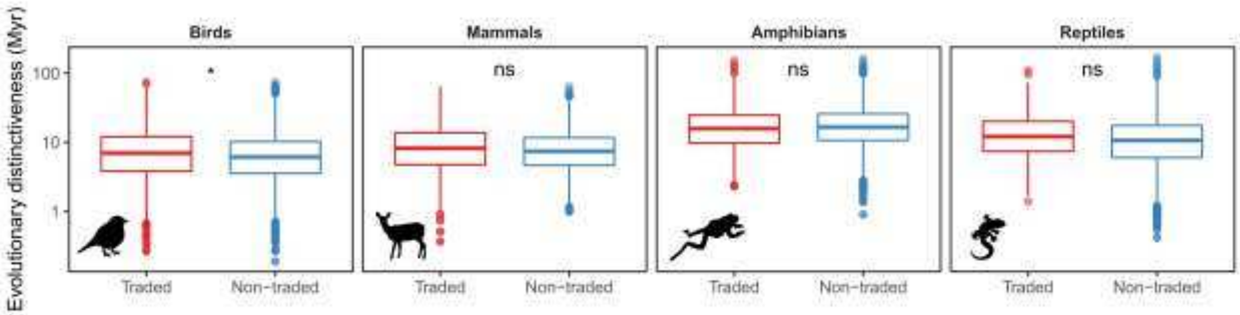

Fig. S5. Variation in evolutionary distinctiveness across traded species. Evolutionary distinctiveness, a measure of evolutionary isolation of lineages, is larger in traded than non-traded birds. This metric is not different between traded and non-traded mammals, amphibians, and reptiles. Relationships were assessed using simulation-based phylogenetic ANOVA of Garland et al. (51). The y-axis is log transformed.

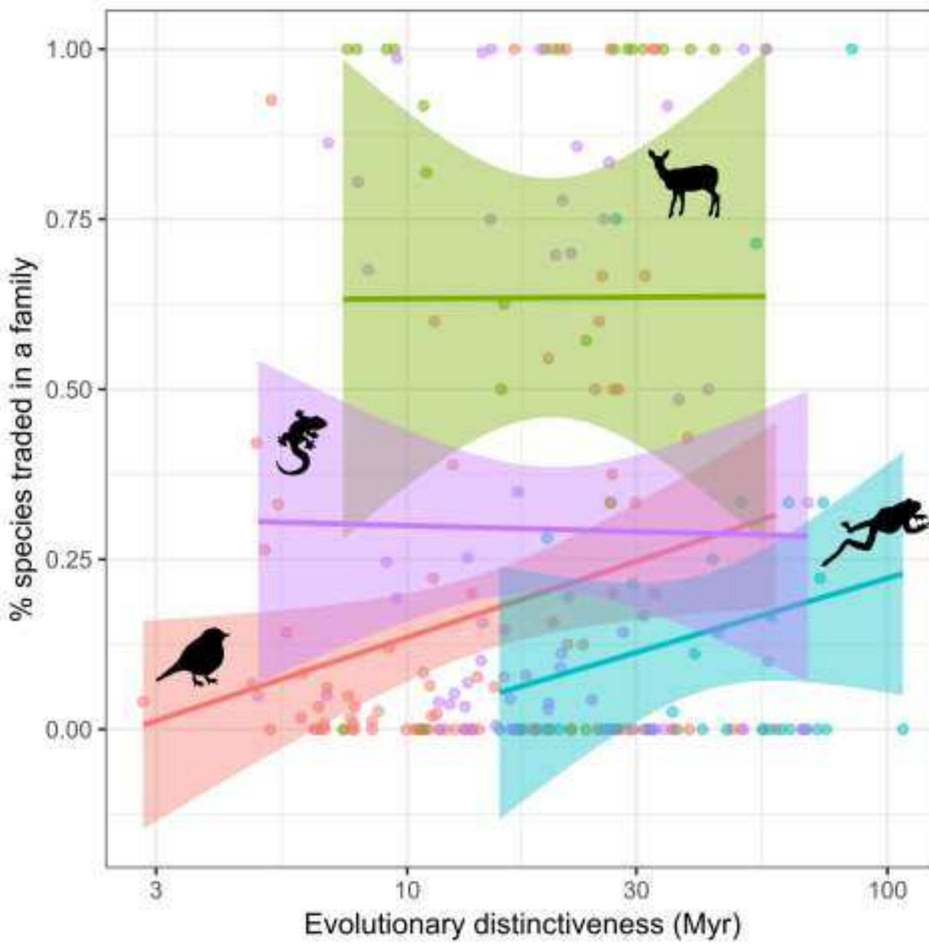

Fig. S6. Relationship between evolutionary distinctiveness and proportion of species traded in families. Birds are the only group in which mean family-wide evolutionary distinctiveness predicts the proportion of traded birds (linear model: slope = 0.18, P-value = 0.01). Each dot represents a family, and the lines indicate the fit of linear relationships. Red is for birds; turquoise, reptiles; purple, amphibians; green, mammals.

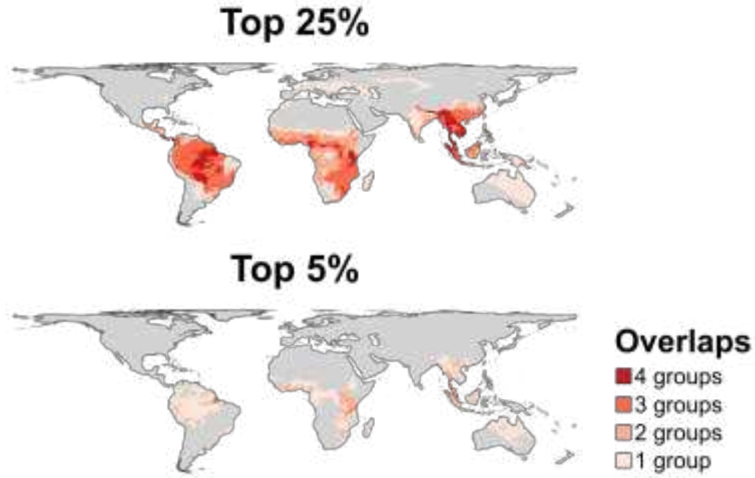

Fig. S7. Geographical overlap in hotspots of wildlife trade across vertebrate groups (birds, mammals, amphibians, and reptiles). Hotspot areas are indicated as the top 25% and top 5% largest number of traded species per cell globally. Cells in which hotpots overlap across taxonomic groups are shown in shades of red (i.e., dark red denotes overlapping hotspots across all four vertebrate groups). Grey areas represent the absence of hotspot.

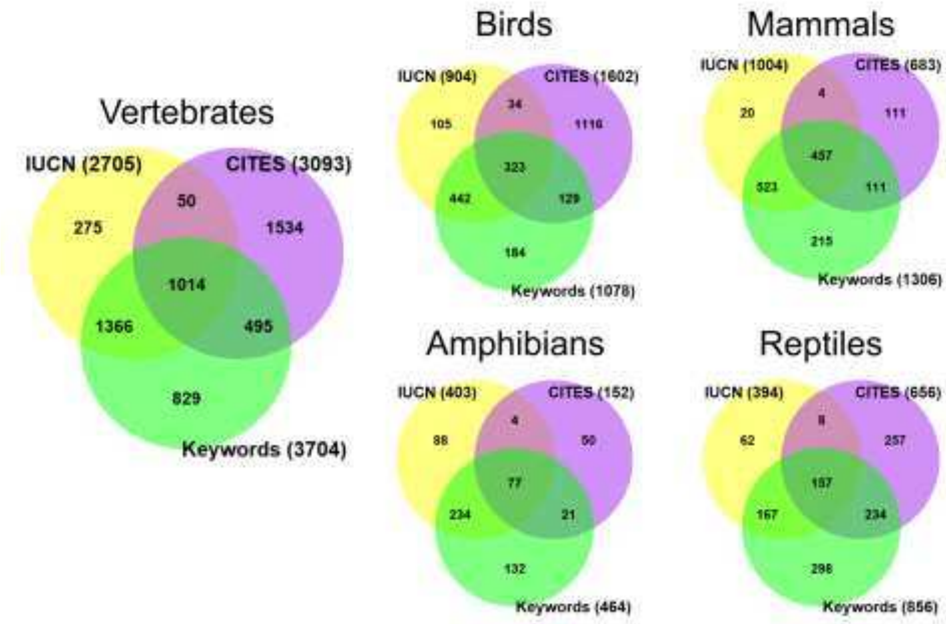

Fig. S8. Venn diagram showing the number of traded species in our database in accordance with the sources. CITES are those species present in any one of the three CITES appendices. IUCN are those species threatened by hunting & collecting terrestrial animals (subcategory intentional use). Keywords are those species found using data mining algorithm that searches for keywords throughout the entire text of a species' IUCN assessment. See methods in the main text for further information.

Supplementary Tables:

Table S1. Summary of wildlife trade in terrestrial vertebrates. Total number of species and families traded in each taxonomic group. Values between parentheses represent percentage of species (or families) traded relative to the total number of species (or families) in each taxonomic group. Summary across all taxonomic groups is given in the column "Vertebrates".

	Birds	Mammals	Amphibians	Reptiles	Vertebrates
Species traded	2,345 (22.8%)	1,441 (26.6%)	609 (9.4%)	1,184 (12.4%)	5,579 (17.6%)
Families traded	108 (54.5%)	110 (80.9%)	41 (54.7%)	53 (72.6%)	312 (64.7%)
Families <50% species traded	32 (16.2%)	69 (50.7%)	4 (5.3%)	23 (31.5%)	128 (26.6%)

Table S2. Distribution of wildlife trade across threat status according to the International Union for Conservation of Nature Red list of Threatened Species. Summary across all taxonomic groups is given in the column Taxa, "Vertebrates". DD=Data Deficient; NA=Not assessed; LC=Least Concern; NT=Near Threatened; VU=Vulnerable; EN=Endangered; CR=Critically Endangered.

Taxa	Threat status	N	N traded (%)
Birds	DD	60	11 (18.3%)
Birds	LC	7872	1293 (16.4%)
Birds	NT	971	385 (39.6%)
Birds	VU	741	349 (47.1%)
Birds	EN	417	199 (47.7%)
Birds	CR	217	108 (49.8%)
Mammals	DD	740	68 (9.2%)
Mammals	LC	3172	641 (20.2%)
Mammals	NT	340	137 (40.3%)
Mammals	VU	512	253 (49.4%)
Mammals	EN	461	226 (49%)
Mammals	CR	195	116 (59.5%)
Amphibians	DD	1435	42 (2.9%)
Amphibians	LC	2555	310 (12.1%)
Amphibians	NT	398	49 (12.3%)
Amphibians	VU	676	92 (13.6%)
Amphibians	EN	868	74 (8.5%)
Amphibians	CR	552	42 (7.6%)
Reptiles	DD	744	49 (6.6%)
Reptiles	LC	2947	465 (15.8%)
Reptiles	NT	288	70 (24.3%)
Reptiles	VU	307	80 (26.1%)
Reptiles	EN	377	103 (27.3%)
Reptiles	CR	181	40 (22.1%)
Reptiles	NA	4719	377 (8%)
Vertebrates	DD	2979	170 (5.7%)
Vertebrates	LC	16546	2709 (16.4%)
Vertebrates	NT	1997	641 (32.1%)
Vertebrates	VU	2236	774 (34.6%)
Vertebrates	EN	2123	602 (28.4%)
Vertebrates	CR	1145	306 (26.7%)
Vertebrates	NA	4719	377 (8%)

Table S3. List of vertebrate families assessed. Number of species, traded species and proportion of traded species per family.

See attached supplement file: Supp_Inf_Table 3_trade_family.xls

Table S4. Phylogenetic analysis of variance (ANOVA) testing for differences in body size between traded and non-traded species. In the column Threat status, "All" denotes the results of ANOVAs performed including all species in a given taxonomic group, regardless of their threat status. Threat status according to the International Union for Conservation of Nature Red list of Threatened Species. DD=Data Deficient; LC=Least Concern; NT=Near Threatened; VU=Vulnerable; EN=Endangered; CR=Critically Endangered.

Taxa	Threat status	F-value	P-value
Amphibian	All	154.6	<0.001
Amphibian	DD	0.8	ns
Amphibian	LC	42.6	<0.05
Amphibian	NT	43.7	<0.001
Amphibian	VU	76.7	<0.001
Amphibian	EN	35.8	<0.01
Amphibian	CR	8.6	ns
Bird	All	1421.8	<0.001
Bird	DD	13.6	<0.01
Bird	LC	420.9	ns
Bird	NT	329.4	<0.001
Bird	VU	297.7	<0.001
Bird	EN	117.5	<0.001
Bird	CR	51	<0.001
Mammal	All	4205.2	<0.001
Mammal	DD	115.3	<0.001
Mammal	LC	2015.6	<0.001
Mammal	NT	278.2	<0.001
Mammal	VU	421.5	<0.001
Mammal	EN	391.7	<0.001
Mammal	CR	141.3	<0.001
Reptile	All	877	<0.001
Reptile	DD	46.8	<0.01
Reptile	LC	364.3	<0.001
Reptile	NT	14.5	ns
Reptile	VU	60.5	<0.001
Reptile	EN	24.9	ns
Reptile	CR	24.6	<0.01

Table S5. Predicted future traded species. Probability of a species being traded in the future based on body size, evolutionary distinctiveness, phylogenetic relatedness, and the proportion of species traded in respective families. All species that have above 50% probability of future trade for at least one assessment technique are provided.

See attached supplement file: Supp_Inf_Table 5_predicted_future_traded.xls

Table S6. Spatial correlation between traded species richess and total species richness across taxonomic groups. Correlations were calculated using Pearson's correlation coefficient. Significance of Pearson's correlations were assessed using Dutilleul's (61) modified t-test to account for spatially independent degrees of freedom.

Class	Coeff.	P-value
Amphibians	0.81	<0.001
Birds	0.9	<0.001
Mammals	0.84	<0.001
Reptiles	0.66	<0.001

Table S7. Summary of trade across global biogeographical regions. Proportion of traded species is relative to the total number of species in a region. Proportion of pet- or product-traded species is relative to the total number of traded species in a region. Note that some species can be traded as both pets and products. Realms classification follows Holt et al. (41), and biomes classification follows Olson et al. (40).

See attached supplement file: Supp_Inf_Table 7_trade_biogeographic_regions.xls

Table S8. Types of wildlife trade across birds, mammals, amphibians, and reptiles. Total number of species and families traded in each taxonomic group as pets and as products. Values between parentheses represent the percentage of species (or families) traded as pets or as products relative to the total number of traded species (or traded families) in each taxonomic group. Summary across all taxonomic groups is given in the column "Vertebrates". Note that percentages do not add up to 100% because 1) for some species it is unknown as to whether they are traded as pets or products, and 2) some species can be traded both as pets and as products.

	Birds	Mammals	Amphibians	Reptiles	Vertebrates
Species traded as pets	1054 (44.9%)	485 (33.7%)	312 (51.2%)	576 (48.6%)	2427 (43.5%)
Species traded as products	1467 (62.6%)	1298 (90.1%)	190 (31.2%)	407 (34.4%)	3362 (60.3%)
Families traded as pets	63 (58.3%)	64 (58.2%)	38 (92.7%)	9 (17%)	174 (55.8%)
Families traded as products	90 (83.3%)	106 (96.4%)	25 (61%)	8 (15.1%)	229 (73.4%)

Table S9. Keywords used for mining trade data from IUCN species' assessments. The asterisk (*) symbol was used to broaden a search by finding words that start with the same letters. For instance, ceremon* will find ceremony and ceremonies.

Keywords			
animal parts	game hunt	medicin*	sold
bird trade	game-hunt	merit release	song bird*
bird-trade	game species	ornament*	songbird*
bush meat	gift	over harvest*	song-bird*
bushmeat	human consumption	over-harvest*	sought
bush-meat	human subsistence	overexploit*	trade*
cage	hunters	over-harvest*	traffick*
cage bird*	hunted	pet*	trap*
cagebird*	hunting	pet trade	trophy*
cage-bird*	international trade	pet-trade	trophy hunt*
ceremon*	ivory	poach*	use and trade
clothes	jewellry	protei*	wild meat
craft	jewelry	ritual*	wild-meat
crime	luxury	sale*	wildlife crime
fur	luxury meat	scales	
game animal	market*	seizure	
game-animal*	mascot*	sell*	

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