Global patterns of vulnerability to wildlife exploitation in tropical birds and mammals

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Abstract

Wildlife exploitation is one of the most pervasive anthropogenic pressures in tropical ecosystems and a major driver of vertebrate population declines, yet global assessments of species vulnerability to hunting remain spatially imprecise and methodologically inconsistent. We combine exposure to hunting with species-specific sensitivity and adaptive capacity to deliver a spatially explicit pantropical vulnerability assessment for 6,338 bird and 3,837 mammal species across three exploitation purposes: direct consumption, product trade, and pet trade. We computed both species-level vulnerability across each species' range and assemblage-level vulnerability across the tropics. Phylogenetically, the most vulnerable groups include large herbivores, pangolins, medium- and large-sized birds, ground-dwelling birds, and primates, with primates showing discrepancy compared to the IUCN Red List assessments for the Indomalayan realm. At the assemblage level, vulnerability hotspots emerge across Sundaland, southeastern China, western and southern Africa, the Atlantic Forest, and the southern Gran Chaco. Spatial patterns are broadly congruent across taxa and exploitation purposes, but regional divergences arise, particularly for birds on islands and for mammals in New Guinea and the Neotropics. Our framework provides a standardized, flexible, and updatable tool to complement existing assessments and support conservation prioritization of areas and taxa under hunting pressure across the tropics.

Main

For humans, hunting is among the oldest known practices which, combined with an exceptional capacity for innovation, allowed our species to expand from the savannahs of Africa to the dense tropical forests of Sri Lanka or the Amazon basin [1–3]. Yet, this age-old practice comes at a cost. When unsustainable, hunting becomes one of the primary, yet most underestimated, drivers of biodiversity loss [4,5]. In tropical forests, home to exceptional and irreplaceable biodiversity [6], hunting is driving local population declines of birds and mammals (i.e., defaunation; [7,8]) and contributing significantly to species extinctions [9,10].

Accurately identifying where hunting occurs, and which species are affected is essential for achieving the 2030 targets of the Kunming–Montreal Global Biodiversity Framework. Previous efforts have been constrained either by limited data availability (e.g., [11,12]) or by a lack of reliable and spatially explicit information on hunting pressure (e.g., [13,14]). Trait-based vulnerability assessments provide a complementary line of evidence by addressing different limitations through the systematic integration of species' biological, morphological, and ecological traits. Originally developed to assess species vulnerability to climate change [15], the vulnerability assessment framework was later refined to capture spatial variation [16] and expanded to evaluate impacts from pollution [17] or multiple threats in insular ecosystems [18]. It quantifies vulnerability through three components: (i) exposure to single or multiple threats, (ii) sensitivity based on species-specific intrinsic traits, and (iii) adaptive capacity, reflecting the ability of species to cope with and respond to threats. Combining these three components into a single vulnerability metric would help overcome the current limitation of vulnerability indicators for large-scale hunting, as the most common indicators focus either on areas where hunting might occur [19], or on areas where species threatened by hunting are found [13], but no existing metric combines these two pieces of information: where hunters are likely to hunt and which species are likely to be targeted more by hunters at pantropical scale.

Hunting is particularly well-suited to trait-based vulnerability assessments, as it is neither spatially or biologically random: hunting pressure spatially concentrates in accessible areas [8,20–23] and particularly targets species with a certain set of traits [7,24] (but see [25] for an example applied to hunting). Hunted species are targeted for distinct purposes, including direct consumption (here referring to subsistence hunting), the pet or product trade. In turn, the scale of wildlife use can be local (subsistence or local trade), or can extend up to the national or international markets [7,10]. Subsistence hunting generally focuses on large-bodied, locally abundant species that maximize returns per unit effort [7,14,24] whereas species targeted for trade are often selected for rarity, distinctive morphology, conspicuous coloration, or phylogenetic distinctiveness, traits associated with higher market value [24,26,27]. Because these hunting motivations are linked to well-established trait combinations (e.g. body mass or plumage), trait-based assessments, particularly for birds and mammals, offer a promising framework for evaluating species' vulnerability to hunting.

Building on this premise, we present the first spatially explicit, trait-based assessment of vulnerability to hunting for 6,338 tropical bird and 3,837 mammal species, the two most overexploited taxa in the tropics [28,29]. We combined a recent pantropical map of exposure to hunting pressure [23] with species sensitivity and adaptive capacity derived from biological, ecological, and morphological traits, phylogenetic information, and empirical data on hunting, trapping and trade. Sensitivity was estimated using documented evidence of subsistence and commercial hunting [30] and trait-based predictions of the likelihood that species are hunted for subsistence, the pet trade, or product trade (see Fig. 1 and methodological details in Fig. S1 & S2). Separate sensitivity scores were calculated for each of these three hunting purposes. Adaptive capacity was quantified using traits related to detectability, accessibility, and resilience, including activity period, habitat use, mobility, dispersal ability, reproductive rate, and geographic range size. For each species, vulnerability was computed as Vulnerability = Exposure + Sensitivity − Adaptive Capacity, with each component rescaled to [0, 1], yielding a score ranging from −1 (least vulnerable) to 2 (most vulnerable). Exposure was based on a map of hunting pressure rescaled to 20 x 20 km resolution[23], whereas sensitivity and adaptive capacity were calculated at the species level. (Fig. 1). Exposure reflects local hunting pressure, Sensitivity the likelihood of being targeted, and Adaptive Capacity the species' ability to withstand offtake. Two summary metrics were derived: a species-level score (mean Vulnerability across all spatial units within the species' Area of Habitat AoH [31], restricted to species with ≥ 90% AoH overlap with the exposure layer) and an assemblage-level score (mean Vulnerability across all species occurring in each 20 x 20 km spatial unit). Both metrics are interpreted in relative terms only, as raw scores are not comparable across taxa or hunting purposes. Subsequently, we assessed whether vulnerability scores concentrated for certain taxonomic families and orders, and ranked species and areas according to vulnerability scores to derive species prioritization lists and pinpoint vulnerability hotspots. Finally, species-level scores were validated against information from IUCN Red List assessments by classifying species as not threatened by hunting, threatened by hunting but not globally threatened with extinction, or threatened by both hunting and extinction.

Results

Species-level Vulnerability

For mammals, species-level Vulnerability scores ranged from (Mean ± SD) 0.42 ± 0.24 (pet trade) to 0.51 ± 0.29 (product trade), and 0.59 ± 0.39 (subsistence hunting), with strong phylogenetic structuring across all purposes (Fig. 2). Pet trade maximum Vulnerability was concentrated in primates, pangolins, and carnivores, while product trade and subsistence hunting showed broader phylogenetic distributions in Vulnerability values spanning primates, bats, large herbivores, elephants, and pangolins. Vulnerability showed significant phylogenetic signal across all purposes (all $p < 0.01$), with high Pagel's λ (pet: 0.96; product: 0.96; subsistence: 0.98) indicating deep node conservatism, and Blomberg's K below 1 (pet: 0.05; product: 0.10; subsistence: 0.19), and Moran's I confirming a gradient of increasing conservatism from pet to subsistence hunting (pet: 0.72; product: 0.80; subsistence: 0.83). Vulnerability ranking discriminated significantly among IUCN threat categories (all pairwise $p < 0.001$), with ordinal regression explaining 21%, 39%, and 40% of variance for pet trade, product trade, and subsistence hunting respectively (Fig. 2B). Species traded as pet reached higher threat categories at lower vulnerability thresholds, with the highest-ranked species, *Elephas maximus* (1.75 ± 0.11), *Pongo pygmaeus* (1.54 ± 0.16), and *Macaca nigra* (1.49 ± 0.02), threatened by both hunting and extinction (Supp. Data 1).

For birds, species-level Vulnerability scores were 0.69 ± 0.23 (subsistence), 0.69 ± 0.18 (product trade), and 0.86 ± 0.25 (pet trade). Maximum values of Vulnerability for pet trade were concentrated in parrots, hornbills, raptors, and certain passerines (mainly Cacatuidae, Musophagidae, Picathartidae); for product trade, high Vulnerability species were more broadly distributed across parrots, Bucerotiformes, Galliformes, Cracidae, and Odontophoridae; and for subsistence hunting top-ranked species were primarily concentrated in Galliformes (Cracidae, Odontophoridae, Phasianidae; Fig. 2D–F). Phylogenetic signal was significant across all purposes (all $p < 0.01$), with the same gradient as mammals: Pagel's λ ranging from 0.80 to 0.86, Blomberg's K from 0.07 to 0.50, and Moran's I from 0.68 to 0.82, all increasing from pet to subsistence hunting. As for mammals, Vulnerability ranking discriminated significantly among IUCN threat categories (all $p < 0.001$; $R^2 = 0.15, 0.29, 0.19$ for pet, product, and subsistence; Fig. 3C–D), though a higher proportion of highly vulnerable bird species were unrecognized by the

IUCN as threatened by hunting, particularly for subsistence hunting (6 of the 20 most vulnerable species; Supp. Data 2). The most vulnerable species were *Triclaria malachitacea* (1.54 ± 0.09), *Polyplectron malacense* (1.48 ± 0.08), and *Crax rubra* (1.69 ± 0.11) for pet, product, and subsistence hunting respectively.

Sensitivity and Adaptive capacity at the species level were highly robust across different weightings and trait compositions, regardless of taxon or hunting purpose (see Supplementary Information, Fig. S17 & S18 for more details)

Spatial patterns of Vulnerability

Indomalayan realm consistently showed the highest assemblage-level Vulnerability scores across all purposes and taxa (birds: 0.86 ± 0.14; mammals: 0.63 ± 0.15), significantly exceeding the Afrotropics (marginal mean differences: 0.085–0.11, $p < 0.001$) and Neotropics (0.14–0.30, $p < 0.001$), with the strongest contrasts observed for mammal subsistence hunting. The Afrotropics in turn ranked significantly higher than the Neotropics across all purposes (0.056–0.29, $p < 0.001$; Fig. 4). Spatial patterns of Vulnerability were consistent across purposes and taxa, with pairwise Spearman correlations among the six maps ranging from 0.78 to 1.00 (all $p < 0.001$; Fig. 5), indicating that the same locations tend to emerge as highly vulnerable regardless of taxon or hunting purpose. High-vulnerability regions consistently combined high Exposure with high Intrinsic Vulnerability (IV = Sensitivity − Adaptive Capacity), while low-Vulnerability regions were more heterogeneous. The Amazon Basin and Central Africa ranked among the least vulnerable due to jointly low Exposure and low IV, whereas other low-ranking regions, like central Borneo, northern Gran Chaco, or northern Myanmar, showed low Exposure despite intermediate IV, suggesting these areas may act as refugia for intrinsically sensitive species that are currently less exposed to hunting. Among intermediate-ranking regions, Caribbean islands and the Philippines showed high Exposure paired with relatively low IV, while most Afrotropical and Indomalayan intermediate-ranking areas showed the inverse pattern of low Exposure combined with higher IV (Fig. 6).

Assemblage-level Vulnerability hotspots (top 20% of all spatial units) were predominantly located in Indomalaya, including southeast China, western India, Sri Lanka, the Malay Peninsula, Java, Sumatra, southern Sulawesi, and coastal Borneo. In the Afrotropics, hotspots concentrated in West Africa, Southern Africa, and the Atsinanana rainforests of eastern Madagascar, while Neotropical hotspots were found in the Caribbean islands, the Atlantic Forest, the southern Gran Chaco, and coastal Gulf of Mexico regions (Fig. 5). Conversely, low-Vulnerability areas (bottom

20%) were largely absent from Indomalaya except in New Guinea, central Borneo, and northern Myanmar, and were most extensive across the Amazon Basin, Central Africa, and the Mesoamerican Biological Corridor. Among the notable regional differences observed across taxonomic groups and hunting practices, we found that mammals hunted for subsistence were ranked as relatively less vulnerable in the Neotropical regions, particularly in the Atlantic Forest and the Mesoamerican Biological Corridor. Additionally, for birds, the vulnerability to exploitation was ranked higher on islands compared to continents (the Caribbean, the Philippines, and northern Sulawesi), with the opposite trend observed in northern Myanmar and the far west of China (Fig. 5). This pattern was not observed in mammals.

Discussion

In this study, we present what is, to our knowledge, the first spatially explicit, species-level assessment of vulnerability to hunting for tropical birds and mammals across the entire pantropical area. Building on a three-dimensional vulnerability framework commonly used in climate vulnerability assessments (e.g., [16]), we combine, (i) fine-scale maps of hunting pressure [23] to define species' Exposure; (ii) species-specific Sensitivity, based on traits linked to the likelihood and scale of being hunted and traded; and (ii) Adaptive capacity, derived from traits that could mitigate the impact of hunting (e.g., reproductive rate, mobility, global population size, see [16–18]). This approach offers three major advantages. First, it provides high-resolution vulnerability maps for one of the most spatially heterogeneous, hard-to-monitor at large scale, and context-dependent pressures in the tropics [32], facilitating the integration of hunting pressure into spatial prioritization and conservation planning. Second, it is customizable and trait-based, allowing for refinement across taxa and regions according to different hypotheses. Finally, our results remain robust across a wide range of methodological changes, ensuring the reliability of our approach for future applications (see Supplementary Information, Fig. S17 & S18).

For mammals, our results confirm prior findings that large-bodied herbivores are among the most vulnerable to hunting [11]. This is consistent with patterns observed in seizure records of illegal wildlife trade [33] and broader megafauna declines [34]. Bird Vulnerability scores followed similar patterns. Larger-bodied birds were more vulnerable across all hunting purposes. Parrots, for example, were the most vulnerable group for pet trade. For product trade and subsistence, ground-dwelling species were more affected. Across both birds and mammals, species-level Vulnerability showed significant and consistent phylogenetic signal regardless of hunting purpose, indicating that susceptibility to overexploitation is not randomly distributed on the tree of life but reflects ancestral trait conservatism. The combination of high Pagel's λ and low Blomberg's K in both taxa reveals that this signal is predominantly concentrated at deep nodes, most certainly at the order and family level, rather than among closely related species, a pattern that is stronger in mammals (λ = 0.96–0.98) than in birds (λ = 0.80–0.86). This is at least partly expected, since our vulnerability score was computed using a sensitivity approach that explicitly incorporates family- and order-level but also traits, such as body size or reproductive rate, which are among the most phylogenetically conserved traits in vertebrates. Nonetheless, these findings are broadly congruent with Scheffers et al. [9], who demonstrated that certain orders and families are disproportionately represented in wildlife trade . A novel aspect in our analysis is that, beyond wildlife trade, hunting for local food consumption consistently showed the strongest phylogenetic signal across both taxa, while Vulnerability for pet trade was the most labile. This gradient likely reflects that subsistence hunting targets body-size and life-history traits deeply conserved across vertebrate phylogenies, whereas commercial hunting additionally incorporates geographic and market-demand components, such as end-use diversity, and commodity-specific traits like coloration or horn morphology [9], that track human preferences rather than evolutionary history, diluting the phylogenetic signal. These results suggest that phylogenetic information is most actionable for prioritizing- species threatened by subsistence hunting, while tackling deleterious effects of commercial trade on species conservation may require demand-specific frameworks operating below the family level. Importantly, we did not integrate data on whether a species is protected (e.g., through national laws or religious beliefs), nor the effectiveness of such protections. While the Conservation Actions Classification Scheme provides species-level conservation measures, it lacks spatial detail and information on effectiveness [26]. This may partly explain mismatches, e.g., giant panda (*Ailuropoda melanoleuca*) shares many traits with hunted mammals but is no longer vulnerable to this threat due to effective protections. Standardized, spatially explicit frameworks like the IUCN Green List [35] or the Conservation Evidence database [36] offer promising tools to address these gaps and could be integrated into future assessments by modulating the final vulnerability score for species with conservation actions in place.

The IUCN Red List, now integrated with CITES data on species trade and hunting status, remains a cornerstone for global biodiversity threat assessments. It has been essential for identifying which species are most affected by trade and where these species occur (e.g., [9]), for highlighting species most likely to be threatened by international trade (e.g., [10]), and for building scoring systems that link wildlife trade to community-level ecological shifts (e.g., [37]). While the Red List and CITES databases are extremely valuable, their effectiveness can be limited by known biases in threat documentation and species coverage ([38,39]; and see Red List Guidelines updates on Threats Classification Scheme (Version 3.3)). However, ongoing efforts to improve data standardization and threat classification could address several of these limitations in the future [40,41]. Considering both the strengths and limitations of the IUCN Red List, we developed our Sensitivity and Adaptive capacity scores by combining its information with a trait-based scoring system based on literature-based hypotheses about species' responses to hunting. Despite using a limited set of traits, our models performed well, especially for birds, where phylogeny explained less variance, likely reflecting less data gaps in trait databases that can be linked to subsistence or commercial hunting compared to mammals (see Supplementary Information). For mammals, traits such as trophy value or market rarity, often linked to price, are difficult to quantify but strongly influence hunting pressure [42]. These factors were partially captured through the phylogenetic component of our models, but their importance also underscores the current lack of comprehensive trait databases that include characteristics that render species more appealing to hunters (see Supplementary Information, Fig. S6–S16). Our resulting composite vulnerability scores aligned well with IUCN hunting threat categories, even after minimizing the influence of IUCN-derived information (e.g. geographic range size, see Supplementary Information, Fig S18). Overall, species classified as more threatened by hunting (i.e., threatened by hunting and with extinction according to the IUCN) were generally more sensitive and less resilient to hunting, and thus more vulnerable (see Supplementary Information, Fig S9). Hence, our approach can reinforce IUCN Red List assessments and provide a first indication of extinction risk category upgrading or assignment for species with outdated assessments or that are data deficient, respectively [41]. While Morton et al. [43] already demonstrated that population declines due to wildlife trade are stronger in species with a higher extinction risk category, here we also provide evidence that species vulnerable to subsistence hunting but that are not necessarily traded can also be threatened. Importantly, our framework allows for the identification of species not currently known to be used for subsistence or traded, but that share key traits with known target species. Some examples include the Kashmir Gray Langur (*Semnopithecus ajax*) or Kinda Baboon (*Papio kindae*) for mammals, and Sri Lanka Junglefowl (*Gallus lafayettii*) or Spot-winged Wood-quail (*Odontophorus capueira*) for birds.

These species are assigned high vulnerability scores, and should be tracked closely in order to prevent future threats from hunting activities (see also [14]).

At the regional level, the top 20% most vulnerable spatial units were concentrated in the Indomalayan realm, notably southeast China, western India, Sri Lanka, the Malay Peninsula, Java, Sumatra, southern Sulawesi, and coastal Borneo. In the Afrotropics, hotspots included West Africa, Southern Africa, and eastern Madagascar. In the Neotropics, vulnerable zones included the Caribbean, Atlantic Forest, and Gulf of Mexico coast. In contrast, low-vulnerability areas (bottom 20%) were rare in Indomalaya (mainly New Guinea, central Borneo and Northern Myanmar), more common in Central Africa (see [25]), and most extensive in the Amazon Basin, Honduras, and northeastern Nicaragua. Our vulnerability maps differ notably from existing hunting threat maps based on IUCN Red List (e.g., [13,14]), which often assume uniform threat levels across species' entire ranges and consequently do not capture local variation on hunting risk. Our results better reflect ecological realities and align with prior regional studies in West Africa [44] and in Southeast Asia [45], and match patterns of illegal hunting in China [46]. While few spatial assessments exist for South America, Bogoni et al. [19] used theoretical relationships to estimate hunting pressure, an approach more comparable to our exposure layer than our full vulnerability model. Their findings, which suggest high hunting pressure in the Amazon Basin and low pressure in the Atlantic Forest, contrast with our results and previous studies [47–50], and could differ for various reasons, such as not focusing only on forest ecosystems or not accounting for the specific types of species present in each location, unlike our approach. Ultimately, our integrated vulnerability framework, combining Exposure, Sensitivity, and Adaptive capacity, reveals consistent global patterns of hunting threat. Vulnerability decreased from Indomalaya to the Neotropics, a gradient that mirrors observed late-Quaternary declines in biomass and community downsizing [51], reinforcing the ecological plausibility of our approach. Additionally, by decoupling Sensitivity - Adaptive capacity (i.e., Intrinsic Vulnerability (IV)) and Exposure, our approach identified areas where species known to be threatened by hunting are not currently vulnerable due to their remote distribution. This is notably the case for regions such as central Borneo and New Guinea, which emerge as potential refugia for threatened species. These findings also highlight limitations of the IUCN Red List when used to spatialize threats, as it may overestimate risk in areas where exposure is minimal. Conversely, regions characterized by high Exposure, but low assemblage-level Vulnerability may warrant further investigation: they could represent barriers to range shifts by hunted species under climate change, or alternatively, indicate areas where the most intrinsically vulnerable species have already been locally extirpated.

As Tulloch et al. [52] highlighted nearly a decade ago, mapping threats at regional and global scales has become increasingly common, using a large set of methodologies. Some approaches are based on species distributions and their reported threats, such as IUCN Red List-based maps [13,53,54]. Others focus on directly mapping threats, often using remote sensing to assess habitat loss or degradation [55,56], natural hazard data [57], or more integrated frameworks combining exposure, sensitivity, and adaptive capacity, as we did in this study [16,17]. Although our goal was not to explicitly produce spatial conservation prioritization maps aligned with the Kunming–Montreal Global Biodiversity Framework, our vulnerability maps can support such planning. We acknowledge ongoing debates around global priority mapping, which has been criticized as overly technocratic and disconnected from local knowledge, practices, and cultural contexts [58]. These concerns are especially relevant for hunting, a highly context-dependent activity shaped by local beliefs, taboos, and socioeconomic conditions [32,59,60]. Our analysis does not account for fine-scale socio-economic factors — such as local wealth, product prices, or hunter density — widely recognized as important drivers of hunting pressure [61]. Nevertheless, by applying a vulnerability framework at fine spatial and species-specific resolution, we provide one of the most comprehensive assessments of tropical hunting pressure to date, yielding outputs adaptable by practitioners and policymakers to local needs. Refining individual components, by replacing binary distributions with abundance data, incorporating more granular hunting intensity measures, or integrating volume-based trade records, would further strengthen the framework at regional or national scales.

This study presents the first pantropical, species-specific assessment of vulnerability to hunting, integrating exposure, sensitivity, and adaptive capacity into a unified framework. While local protection measures and cultural taboos remain to be incorporated, the vulnerability maps and species rankings provide actionable tools for conservation prioritization, and future work should integrate socio-cultural dynamics to further refine global assessments.

Electronic Supplementary Information

Supplementary data containing species-level metrics, assemblage-level vulnerability rasters, and all code necessary to reproduce the analyses and figures are available at the following Zenodo repository: https://doi.org/10.5281/zenodo.19452348. The supplementary materials are organized into three folders. The species-level dataset folder contains Excel files with species-level vulnerability metrics. The landscape-level folder contains rasters of either the spatial distribution of vulnerability across each species' area of habitat or the assemblage-level vulnerability, computed as the mean across all co-occurring species. The R-scripts folder contains two R projects: S1 covers the computation of Sensitivity and Adaptive Capacity scores and the robustness analyses, and S2 covers vulnerability computation, mapping, and phylogenetic analyses.

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Methods

1. Data collection

We selected mammal and bird species whose distributions intersect the pantropical forest zone, as defined by Potapov et al. [62] (i.e. areas with > 20% forest cover covering the (sub)tropics) Global range maps were obtained from the IUCN Red List [30] for mammals and from the BirdLife International data portal [63] for birds; for migratory bird species, only resident ranges were retained. This filtering resulted in a final dataset of 4,450 mammal species and 8,106 bird species. For all selected species, we retrieved the information required to compute the sensitivity and adaptive capacity components in the vulnerability framework, which were based on information on hunting status, species traits, and area of habitat.

1.1. Hunting status

Information on species hunting status was compiled by combining data from the IUCN Red List [30] and Hughes et al. [37]. For each species, we retrieved information on (i) hunting purpose (*end uses*) and (ii) the geographic scale of hunting from the IUCN Red List. End uses were extracted from the IUCN Red List using the General Use and Trade Classification Scheme (version 1.0) and correspond to the number of unique IUCN use codes (1–18) associated with each species. Based on the combination of *end use* information and geographic commercial scale, we classified species into three independent binary hunting categories following commonly used classifications in the literature (e.g., [9]): “subsistence”, “product trade”, and “pet trade”. Species were classified as hunted for “subsistence” if they were explicitly reported as hunted for meat consumption (IUCN *code 1*) and for *subsistence*. Species were classified as hunted for the “pet trade” if they were associated with the IUCN pet trade code (*code 13*) and reported at least in one geographic commercial scale. Species were classified as hunted for “product trade” if they were associated with IUCN use codes other than *code 13* and reported at least at one geographic commercial scale. Species not meeting these criteria were classified as not hunted for the corresponding category. Classifications for “pet trade” and “product trade” were cross validated and complemented using the information provided by Hughes et al. [37]. Information on global extinction risk (Least Concern, Vulnerable, Endangered, Critically Endangered) and hunting threat status (i.e. whether a species is identified as threatened by hunting) was also extracted from the IUCN Red List. This process resulted in six distinct datasets corresponding to the combination of two taxa (birds and mammals) and three hunting purposes (“subsistence”, “pet trade”, and “product trade”). Although each dataset includes the full species list for the focal taxon, they differ in the type of hunting information they contain. Specifically, the “subsistence” datasets include binary information (1: hunted *vs* 0: non-hunted) on whether species are hunted for “subsistence”, whereas the “pet trade” and “product trade” datasets additionally include information on the geographic commercial scale (*local*, *national*, and/or *international*). Because the IUCN Red List does not distinguish between hunting for direct consumption or local trade, species reported as hunted for subsistence were considered subject to both direct use and local commercialization. For “product trade”, datasets further include the number of documented *end use* per species. These purpose-specific datasets were used to parameterize the vulnerability analyses for each hunting objective separately.

1.2. Traits

For birds, morphological and ecological traits were obtained primarily from the AVONET database [64], including body mass, hand-wing index, beak length, tail length, and primary lifestyle. Color elaboration was sourced from Santangeli et al. [27], and corresponds to the mean distance between the colors expressed by a species and the global average color across all species (brown–grey). Population density estimates were obtained from Santini et al. [65], while clutch size and nocturnality were extracted from Marino et al. [66]. Taxonomic information (order and family) and extent of occurrence were obtained from BirdLife [63].

For mammals, body mass, brain mass, foraging stratum, nocturnality, generation length, age at first reproduction, litter size, and number of litters per year were compiled from the COMBINE database [67]. Population density estimates were sourced from Santini et al. [68], and taxonomic information (order and family) and extent of occurrence were obtained from the IUCN Red List [30].

Detailed descriptions of all traits, along with their rationale for inclusion in the vulnerability framework, are provided in Supplementary Information (Fig. S1 & S2).

1.3. Area of habitat

Species distributions were based on area of habitat maps from Lumbierres et al. [31], which provide a refined and more realistic representation of species' distributions by accounting for actual habitat use and reducing commission errors inherent to broad IUCN range maps. These areas of habitat layers were further masked to retain only the pan-tropical portion of each species' distribution and were provided at a spatial resolution of 1/1008° (approximately 100 m at the equator) and aggregated at 20 × 20 km using the nearest-neighbor method.

2. Vulnerability framework

We derived vulnerability scores independently for each taxon and each hunting purpose based on the corresponding datasets described above. Because the following frameworks differ in their underlying information and structure, Vulnerability is not directly comparable across taxa or hunting purposes; they are therefore interpreted only as relative rankings within each taxon × purpose combination. Below, we detail the vulnerability framework applied to each of these combinations.

2.1. Exposure

Exposure to hunting was defined identically for both taxa and across the three hunting purposes. We used the hunting pressure map developed by Philippe-Lesaffre et al. [23], which estimates the predicted probability that a 1 × 1 km spatial unit is subject to hunting across the pan-tropical region for 2015. This map is based on a random forest binary classifier trained on a global dataset of hunted versus non-hunted sites, integrating accessibility, socio-economic, and ecological predictors. The training data encompass hunting events involving both birds and mammals, across subsistence and trade purposes, and including both legal and illegal activities.

To align the exposure layer with species distributions, the hunting pressure map was used as the spatial reference. For each species, Exposure (i.e., hunting pressure) was extracted for all 1 × 1 km spatial units overlapping its area of habitat. spatial units where the species was present were assigned the corresponding Exposure, whereas cells outside the species' distribution were assigned a value of zero. Species-level exposure was then aggregated to a 20 × 20 km resolution by calculating the mean hunting pressure across all occupied spatial units.

Importantly, Exposure is independent of species identity and depends solely on spatial location. Consequently, multiple species occurring within the same spatial unit share the same exposure value for that cell.

2.2. Sensitivity

Sensitivity is a species-level metric, with a single value derived for each species separately for each taxon and hunting purpose, reflecting the distinct mechanisms by which species are targeted by hunters. This score is assumed to be constant across a species' area of habitat and is based solely on intrinsic species characteristics. Sensitivity represents the likelihood that a species will be targeted (and continue to be targeted) if hunting occurs in an area where the species is present, with higher values indicating greater targeting pressure.

2.2.1. Probability of a species being hunted

Although information exists on which species are currently hunted and for which purposes, our objective was to refine this binary information by estimating continuous sensitivity scores that capture how likely a species is to be targeted based on its traits and evolutionary history, including for species not currently documented as hunted. This approach allows the identification of species potentially sensitive to hunting now or in the future, despite gaps in hunting or trade records.

Sensitivity was defined differently for each hunting purpose. For "subsistence" (direct consumption), Sensitivity was based solely on the predicted probability that a species would be hunted for "subsistence". For the "pet trade", Sensitivity combined the probability of being hunted for commercial purposes with information on the geographic commercial scale. For the "product trade”, Sensitivity incorporated the probability of being hunted for commercial purposes, the number of documented *end uses*, and the geographic commercial scale. The probability of being hunted constitutes the common component across all Sensitivity scores, but probabilities were modelled separately for each purpose and taxon (Fig S4 & S5).

Trait selection reflected purpose-specific hypotheses. For “subsistence”, body mass and population density were used for both birds and mammals, based on the assumption that species hunted for direct consumption are those maximizing caloric returns [69]. For “pet trade” and “product trade”, we included traits associated with attractiveness or desirability: color elaboration, beak length, and tail length for birds, and brain mass for mammals [27]. Phylogenetic structure was explicitly incorporated to account for shared, unmeasured characteristics among related species that render them attractive but for which there is no systematic account (see Fig. S1 & S2 for more details).

To estimate hunting probabilities, we used a bootstrap resampling approach to generate 100 training–testing dataset pairs, each consisting of 70% training and 30% testing data, stratified by family to ensure taxonomic representation. For each bootstrap iteration, generalized linear mixed-effects models (GLMMs) with a binomial error distribution were fitted using the *glmer()* function in the lme4 R package [70]. Models were trained using binary response variables indicating presence (1) or absence (0) of hunting for each purpose and then used to predict hunting probabilities for all species.

For each species, predicted probabilities were averaged across the 100 bootstrap iterations to obtain mean sensitivity scores for subsistence hunting ($\hat{p}(subsistence)$), pet trade ($\hat{p}(pet)$), and product trade ($\hat{p}(product)$). Separate model structures were fitted for birds and mammals, as follows.

For birds:

$$Subsistence_i \sim log_e(body\,mass_i) + res(density)_i + (1 \mid Order_i/Family_i) + \varepsilon_i$$

$$Pet\,trade_i \sim log_e(body\,mass_i) + res(density)_i + elaboration_i + res(tail\,length)_i + res(beak\,length)_i + (1 \mid Order_i/Family_i) + \varepsilon_i$$

$$Product\,trade_i \sim log_e(body\,mass_i) + res(density)_i + elaboration_i + res(tail\,length)_i + res(beak\,length)_i + (1 \mid Order_i/Family_i) + \varepsilon_i$$

For mammals:

$$Subsistence_i \sim log_e(body\,mass_i) + res(density)_i + (1 \mid Order_i/Family_i) + \varepsilon_i$$

$$Pet\,trade_{i_i} \sim log_e(body\,mass_i) + res(density)_i + res(brain\,size)_i + (1 \mid Order_i/Family_i) + \varepsilon_i$$

$$Product\ trade\ _i \sim log_e(body\ mass_i)\ +\ res(density)_i + res(brain\ size)_i + (1 \mid Order_i/Family_i) + \varepsilon_i$$

To account for allometric relationships, we controlled for body mass when analyzing tail length, beak length, population density, and brain size by fitting linear models between body mass and each trait and using the residuals of these relationships in the models (e.g. positive residuals in the brain-body mass relationship indicate larger brain than expected for a given body mass, and hence higher cognitive capacity, [71]). Model performance was assessed using marginal and conditional R^2 values calculated with the *r2()* function from the performance R package [72]. Detailed results of this modelling approach are provided in the Supplementary Information.

2.2.2. Geographic trade scale and end uses

For species hunted either for "pet trade" or "product trade", we used information on the geographic commercial scale from the IUCN Red List. This information is provided as binary variables indicating whether a species is known to be commercialized for *subsistence*, traded at the *national* level, and/or traded at the *international* level (1 = yes, 0 = no). We incorporated these data under the assumption that species traded across multiple and increasingly broader geographic scales experience higher targeting pressure than species commercialized for *subsistence* or locally. Accordingly, trade scale was categorized as *subsistence* commercialization (score = 1), *national* trade (score = 2), and *international* trade (score = 3). These scores were summed to generate a total trade-scale index ranging from 0 (no recorded trade) to 6 (trade documented at all three geographic scales), which was incorporated into Sensitivity for "pet trade" and "product trade".

Species traded for the "pet trade" are associated with a single *end use*, whereas species hunted for "product trade" may be associated with multiple *end uses*. To account for this difference, we constructed a cumulative trade-scale score for product-traded species by summing trade-scale scores across all relevant product use codes (i.e. all IUCN use codes except code 13). Thus, for the "pet trade", the trade-scale score reflects a single *end use* and its associated geographic commercial scale, whereas for "product trade" it integrates across multiple *end uses* and their associated geographic commercial scale. All trade-scale scores were subsequently normalized using min–max scaling to match the magnitude of the corresponding hunting probability estimates ($\hat{p}(pet)$ and $\hat{p}(product)$).

2.2.3. Sensitivity scoring

Species Sensitivity scores were calculated for each species *i* separately for “subsistence”, “pet trade”, and “product trade” as follows:

$$Sensitivity(subsistence)_i = \hat{p}(subsistence)$$

$$Sensitivity(pet\ trade)_i = \frac{\hat{p}(pet\ trade)_i + \ min - max(scale(pet\ trade)_i)}{2}$$

$$Sensitivity(product\ trade)_i = \frac{\hat{p}(product\ trade)_i + \ min - max(\Sigma scale(product\ trade)_i)}{2}$$

For “subsistence”, Sensitivity is defined solely by the probability that a species is hunted for “subsistence”. For “pet trade” and “product trade”, Sensitivity combines two components: (i) the probability that a species is targeted for that purpose and (ii) the geographic commercial scale. Both components are scaling with min–max to range between 0 and 1, and equal weight is given to targeting likelihood and trade scale. Alternative scoring approaches are provided in Supplementary Information to assess robustness of our framework.

2.3. Adaptive capacity

Adaptive capacity was computed at the species level and was therefore assumed to be constant across each species’ area of habitat and constant across hunting purposes. For both mammals and birds, traits were selected based on their broad availability across species and their hypothesized relevance to a species’ ability to recover from harvesting. Each trait was chosen to represent one of several mechanisms expected to enhance adaptive capacity under hunting pressure. Ordered from lowest to highest presumed importance, these mechanisms include: (1) behaviors that reduce detectability or accessibility to hunters, (2) low fitness costs associated with behavioral avoidance, (3) the ability to disperse away from heavily hunted areas, (4) fast life-history strategies, and (5) the presence of large source populations capable of supporting recolonization.

2.3.1. Birds

For birds, adaptive capacity was described using primary lifestyle, hand-wing index, clutch size, and extent of occurrence. Primary lifestyle was treated as an ordinal variable reflecting accessibility to hunters, with ground-dwelling species assigned the highest accessibility (1), insessorial, generalist, or aquatic species intermediate accessibility (2), and aerial species the lowest accessibility (3). The hand-wing index was used as a morphological proxy for dispersal ability, with higher values indicating greater dispersal potential. Clutch size was included as a proxy for life-history strategy, and extent of occurrence (EOO; km²) represented the availability of large source populations capable of supporting recolonization.

2.3.2. Mammals

For mammals, adaptive capacity was described using foraging stratum, nocturnality, dispersal ability, life-history strategy, and EOO. Foraging stratum was treated as an ordinal variable reflecting accessibility to hunters, with ground-dwelling species assigned the highest accessibility (1), followed by scansorial species (2), arboreal species (3), and aerial species with the lowest accessibility (4). Nocturnality was coded as a binary variable (0 = diurnal, 1 = nocturnal), reflecting the potential for temporal refuge from human activity. Dispersal ability was initially represented by dispersal distance, defined as the distance between an individual's birthplace and its reproductive site (km), capturing the capacity to move away from heavily hunted areas. Life-history strategy was quantified using generation length, age at first reproduction, litter size, and number of litters per year; these traits were combined using a principal component analysis performed with the R function *prcomp()* in R stats. The first principal component, explaining 69.5% of the variance (compared with 16.5% for the second and 12.3% for the third), was retained as a composite measure of reproductive rate. EOO (km²) was included as a proxy for the presence of large source populations and the potential for recolonization.

Adaptive capacity for mammals was calculated as a weighted mean of standardized trait values, with negative weighting applied to foraging stratum to reflect increased accessibility to hunters. Dispersal distance was ultimately excluded from the final formulation because data were unavailable for many species and imputed based on body mass. See Supplementary Information, Fig. S17 & S18, for more details.

2.3.3. Adaptive capacity scoring

Species Adaptive capacity scores were calculated, for each species *i*, in the same way for "subsistence", "pet trade", and "product trade", with different formulas for birds and mammals. Because species-level Adaptive capacity is intended to counterbalance Sensitivity to a given threat—here, hunting—it was defined as a value, with a maximum of 1 and a minimum of 0. Higher values therefore indicate a greater ability to cope with hunting pressure.

For birds:

$$Adaptive\ capacity_i = \frac{A * min - max(primary\ lifestyle_i)\ +\ B * min - max\ (hand\ wing\ index_i)\ + C * min - max\ (clutch\ size_i)\ +}{A + B + C + D}$$

For mammals:

$$Adaptive\ capacity_i = \frac{A * min - max\ (foraging\ stratum_i)\ + B * min - max\ (nocturnality_i)\ +\ C * min - max\ (reproductive\ rate}{A + B + C + D}$$

All trait values were scaled using min–max normalization to preserve their relative distribution across species, such that values ranged between the minimum and maximum observed across species, enabling direct comparison among traits. As not all traits were expected to contribute equally to adaptive capacity, we applied a weighted scoring scheme reflecting their presumed importance, with weights increasing from traits associated with local-scale behavioral responses to those linked to long-term population persistence, i.e., A = 1, B = 2, C = 3 & D = 4. This weighting was motivated by evidence from IUCN Red List assessments, which consistently identify restricted geographic range and low reproductive rate as primary drivers of extinction risk, while dispersal plays an intermediate role, and behavioral traits primarily influence local-scale responses. Robustness analyses exploring alternative weighting schemes are provided in the Supplementary Information.

2.4. Vulnerability

2.4.1. Calculation of species-level Vulnerability per spatial unit

Vulnerability was computed independently for each taxon and each hunting purpose. For each species, computations were restricted to the 20 × 20 km spatial units within tropical forests that intersected its area of habitat for which we extracted the Exposure. spatial units falling outside a species' area of habitat were assigned a Vulnerability of zero and were not considered in next steps. For each species i and spatial unit j where the species occurs, Vulnerability was calculated as:

$$Vulnerability_{ij} = Exposure_j + Sensitivity_i - Adaptive\ capacity_i$$

In this formulation, $Exposure_j$ represents the hunting pressure at spatial unit j and ranges from 0 to 1. $Sensitivity_i$ and $Adaptive\ capacity_i$ are species-level attributes bounded between 0 and 1 respectively. $Vulnerability_{i,j}$ ranged between -1 and 2, from the least to the most vulnerable species or assemblages. During $Vulnerability_{ij}$ calculations, species were progressively excluded due to data limitations. For mammals, $Sensitivity_i$ and $Adaptive\ capacity_i$ could be computed for 3,956 of the 4,450 species, decreasing to 3,697 species after intersecting areas of habitat with the $Exposure_j$. For birds, species numbers declined from 8,106 to 7,829 for "pet trade” and “product trade” and to 7,868 for “subsistence” due to missing trait data; after intersecting areas of habitat with the $Exposure_j$ 6,238 species were retained for “pet trade” and “product trade” analyses and 6,251 for “subsistence”. $Sensitivity_i - Adaptive\ capacity_i$ is referred as $Intrinsic\ Vulnerability_i$ (IV_i) hereafter.

2.4.2. Species-level and assemblage-level Vulnerability

Once Vulnerability scores were calculated for each species in each spatial unit, we derived two summary metrics. Species-level Vulnerability was computed as the mean Vulnerability per species across all 20 × 20 km spatial units within the tropical portion of each species’ area of habitat, capturing overall Vulnerability to hunting within tropical forests. For species-level analyses, we retained only species for which at least 90% of their area of habitats spatial units overlapped with the hunting exposure layer, ensuring consistency with IUCN comparisons and avoiding inflation of Vulnerability scores for species minimally exposed to hunting. This filtering retained 2,477 mammal species and 3,852 bird species for pet and product trade, and 3,862 bird species for subsistence hunting. Vulnerability scores for all species with any portion of their area of habitat overlapping the Exposure layer are provided in the Supplementary Data 1 & 2. assemblage-level Vulnerability was calculated as the mean Vulnerability per spatial unit *j* across all species occurring in that cell (i.e. species with $Exposure_j > 0$), to identify hotspots where high hunting pressure coincides with assemblages of sensitive species with low adaptive capacity. Because Vulnerability was computed independently for each taxon and hunting purpose, species and assemblage-level Vulnerability were estimated separately for “subsistence”, “pet trade”, and “product trade” for mammals and birds, resulting in six distinct analyses (two taxa × three hunting purposes).

3. Further analyses

3.1. IUCN Red List cross-validation

To assess whether our species-level indices (IV and Vulnerability) were consistent with IUCN assessments of hunting, we performed six ordinal regression analyses using the *vgam()* function from the vgam R package [73]. One model was fitted for each combination of taxon (birds or mammals) and hunting purpose ("pet trade", "product trade", or "subsistence"). The IUCN Red List provides two complementary types of species-level information. First, global extinction risk (hereafter IUCN threat status) is expressed as an ordinal category reflecting increasing extinction risk: Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), and Critically Endangered (CR). Second, the Red List documents specific threats affecting species using the IUCN Threats Classification Scheme (version 3.3). Hunting is coded as threat 5.1.1 ("Hunting & collecting terrestrial animals" under "Intentional use, where the species being assessed is the target"). Species were considered threatened by hunting when this code was listed in their threat assessment. Using this information, we derived a three-level ordinal response variable describing hunting-related extinction risk. Species without the hunting threat code were classified as *Not threatened by hunting*, regardless of their IUCN threat status. Species listed as threatened by hunting but classified as LC, NT, or Data Deficient (DD) were categorized as *Threatened by hunting but not threatened with extinction*. Species listed as threatened by hunting and classified as VU, EN, or CR were categorized as *Threatened by hunting and threatened with extinction*. Because the extinction risk of DD species is uncertain, we additionally conducted a sensitivity analysis in which DD species were grouped with the extinction-threatened category. Each ordinal regression tested the relationship between one of our composite indices (either IV or Vulnerability) and this three-level response variable, allowing us to evaluate whether higher index values were associated with increasing IUCN-assessed hunting-related threat.

The models followed the formula:

$$IUCN\ hunting\ threat\ category_{i,k,l}\ \sim IV_{i,k,l}$$

$$IUCN\ hunting\ threat\ category_{i,k,,l}\ \sim Vulnerability_{i,k,l}$$

Each score and category were computed for each species *i*, and models were independently computed for each hunting purpose *k* and taxon *l*. Model assumptions were evaluated using multiple diagnostic tests: the Lipsitz test, Hosmer–Lemeshow test, Likelihood Ratio test of the proportional odds assumption, and Brant test, implemented with the gofcat R package [74]. Residual diagnostics were performed with the DHARMa R package [75].The significance of the relationship between our scoring system and IUCN categories was assessed using the p-values of the model slope estimates and Likelihood Ratio tests comparing the full model with a null model containing only the intercept.

3.2. Statistical analysis

To test for differences in IV or Vulnerability scores across categorical groups (e.g., realm, taxon, hunting purpose), we used linear models computed using the R function *lm()* function in R stats. Post hoc pairwise comparisons were performed using pairwise comparisons of least-squares means with Šidák correction, implemented via the *emmeans*() function from the emmeans R package [76] and the *cld()* function from the multcomp R package [77]. Significance was assessed at $\alpha = 0.05$.

We assessed the phylogenetic signal of species-level vulnerability for each hunting purpose (pet trade, product trade, subsistence) using three complementary metrics computed using the R package phytools [78]: (i) Blomberg's K, which tests whether trait similarity among relatives exceeds random expectation under Brownian motion [79]; (ii) Pagel's λ, estimated by maximum likelihood, which rescales internal branch lengths to quantify how much of the trait variance is explained by phylogenetic structure [80](Pagel 1999); (iii) sparse Moran's I statistic based on a k-nearest-neighbour phylogenetic weight matrix ($k = 50$), which measures local autocorrelation between a species' vulnerability and that of its closest relatives on the tree. Statistical significance for K and Moran's I was assessed by permutation and λ was tested via a likelihood ratio test against a white-noise model ($\lambda = 0$). Phylogenies were extracted from Upham et al. [81] and Jetz et al. [82] and a consensus tree, calculated from 100 random trees, was constructed for each taxon.

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Figures

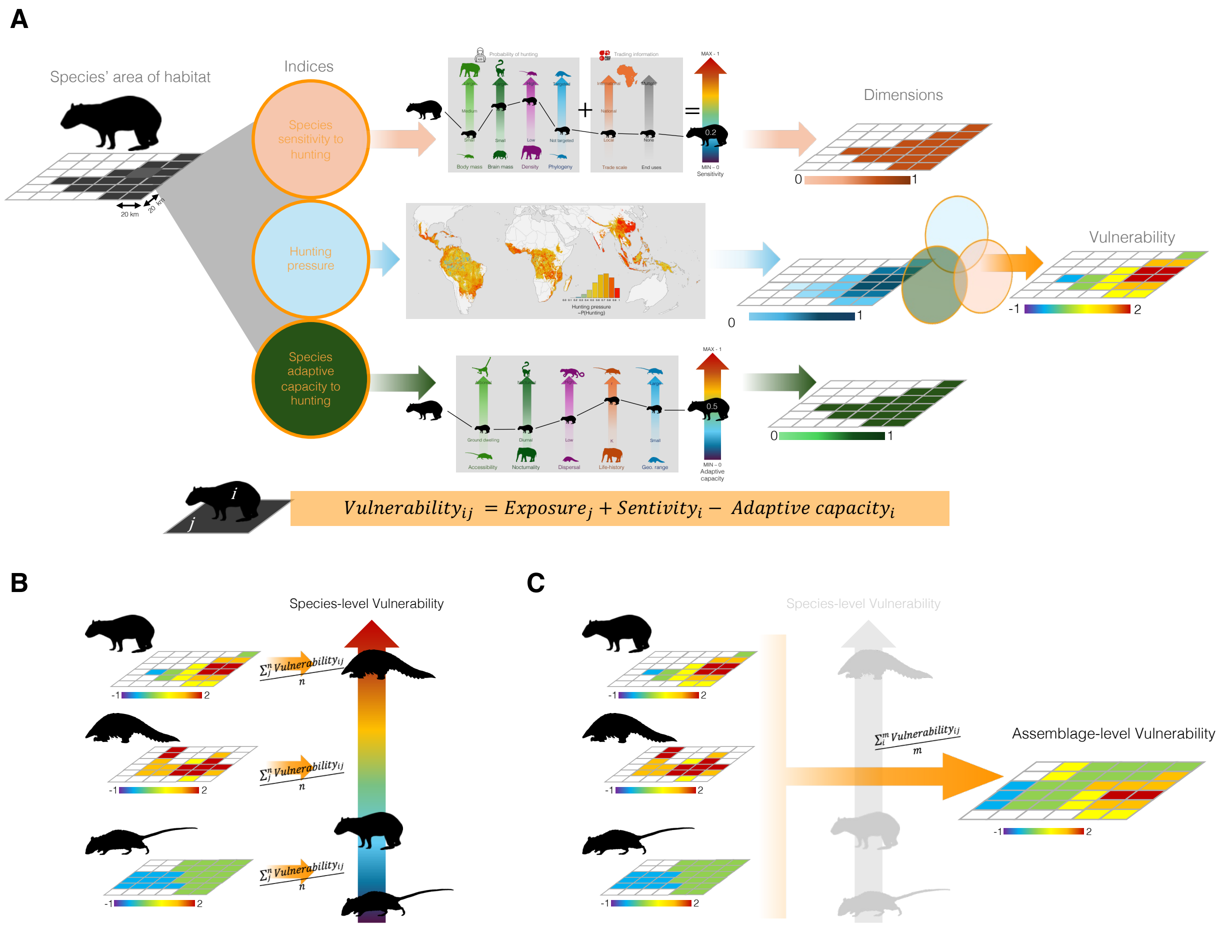


Figure 1. Species-specific and spatially explicit scoring of hunting vulnerability for tropical birds and mammals.

Panel A illustrates the general framework: for each species, a Vulnerability score is computed at each 20 × 20 km spatial unit within its area of habitat (AoH) by combining a spatially explicit measure of Exposure to hunting, corresponding to the predicted probability of hunting occurrence, with two species-specific components (constant across all spatial units within a species' AoH): Sensitivity, reflecting the likelihood of being targeted, and Adaptive Capacity, reflecting the ability to sustain hunting offtake. The resulting Vulnerability score, defined as Exposure + Sensitivity – Adaptive Capacity, is thus resolved at the 20 × 20 km spatial unit level. Panels B and C display two complementary summary metrics derived from this score: the species-level Vulnerability (Panel B), computed as the mean Vulnerability across all spatial units within a species' AoH, and the assemblage-level Vulnerability (Panel C), computed for each 20 × 20 km spatial unit as the mean score across all occurring species. Silhouettes were sourced from PhyloPic.org (T. Michael Keesey, 2025).

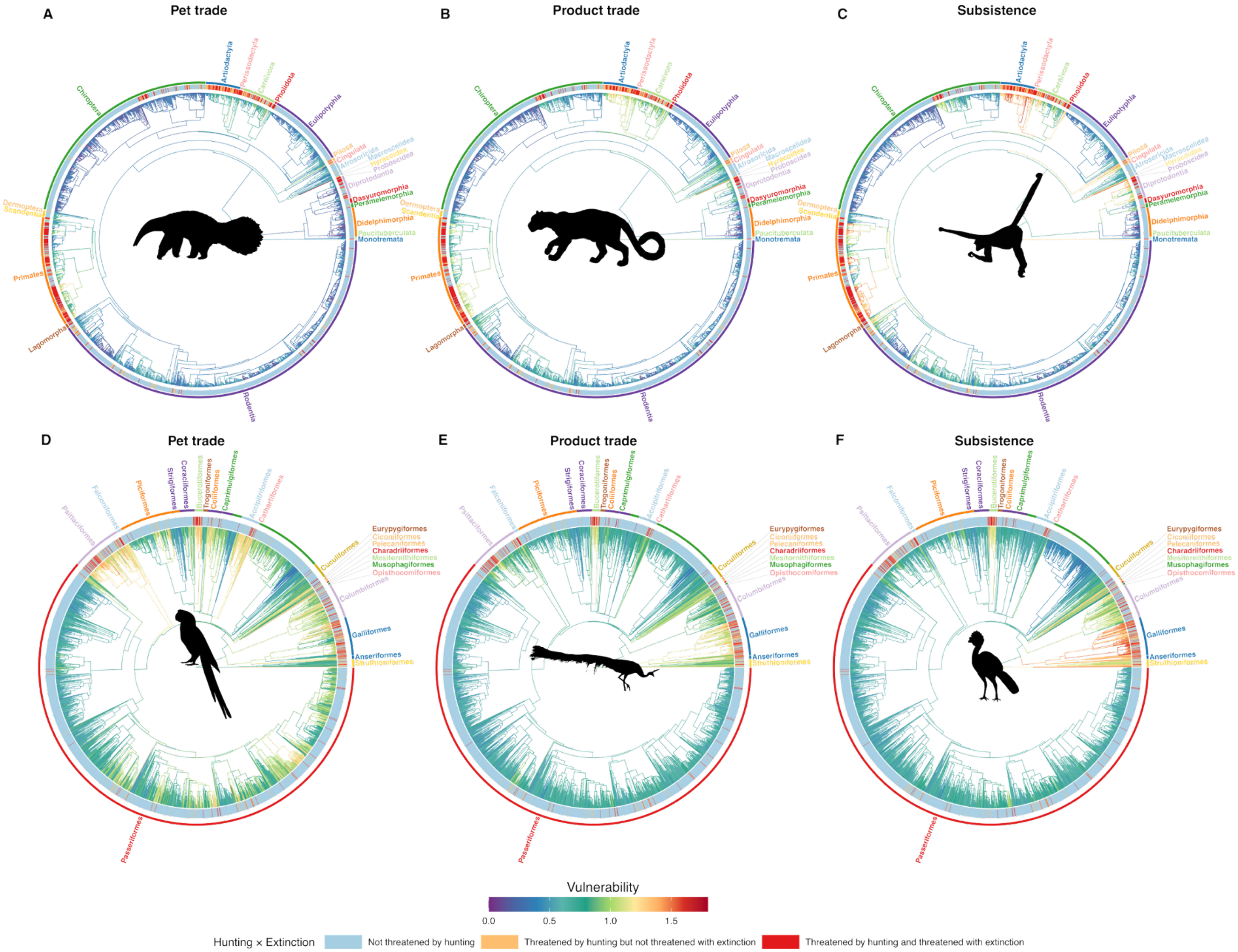

A
Pet trade
B
Product trade
C
Subsistence
Chiroptera
Artiodactyla
Perissodactyla
Carnivora
Pholidota
Eulipotyphla
Pilosa
Cingulata
Afrosoricida
Macroscelidea
Hyracoidea
Proboscidea
Diprotodontia
Dasyuromorphia
Peramelemorphia
Dermoptera
Scandentia
Didelphimorphia
Paucituberculata
Monotremata
Primates
Lagomorpha
Rodentia
D
Pet trade
E
Product trade
F
Subsistence
Psittaciformes
Falconiformes
Piciformes
Strigiformes
Coraciiformes
Bucerotiformes
Trogoniformes
Coliiformes
Caprimulgiformes
Accipitriformes
Cathartiformes
Cuculiformes
Eurypygiformes
Ciconiiformes
Pelecaniformes
Charadriiformes
Mesitornithiformes
Musophagiformes
Opisthocomiformes
Columbiformes
Galliformes
Anseriformes
Struthioniformes
Passeriformes
Vulnerability
0.0
0.5
1.0
1.5
Hunting × Extinction
Not threatened by hunting
Threatened by hunting but not threatened with extinction
Threatened by hunting and threatened with extinction

Figure 2. Vulnerability to hunting across the avian and mammalian phylogenies.

The mammalian phylogeny (A, B, C) and the avian phylogeny (D, E, F) are colored according to species-level Vulnerability scores. Separate panels are shown for each hunting purpose. The outer ring encodes the IUCN Hunting × Extinction threat categories based on IUCN Red List status and threat assessments: species listed as Vulnerable, Endangered, or Critically Endangered and also assessed as threatened by hunting are shown in red (*Threatened by hunting and at risk of extinction*); species listed as Least Concern or Near Threatened but still assessed as threatened by hunting are shown in yellow (*Threatened by hunting but not at risk of extinction*); species assessed as not threatened by hunting are shown in blue (*Not threatened by hunting*). Taxonomic orders are labeled in bold on the outer edge of the tree to highlight phylogenetic structure in vulnerability and threat status. Black and gray colors have been alternated to improve the visibility of order changes. Phylogenies were extracted from Upham et al. [81] and Jetz et al. [82]. Silhouettes were sourced from PhyloPic.org (T. Michael Keesey, 2025).

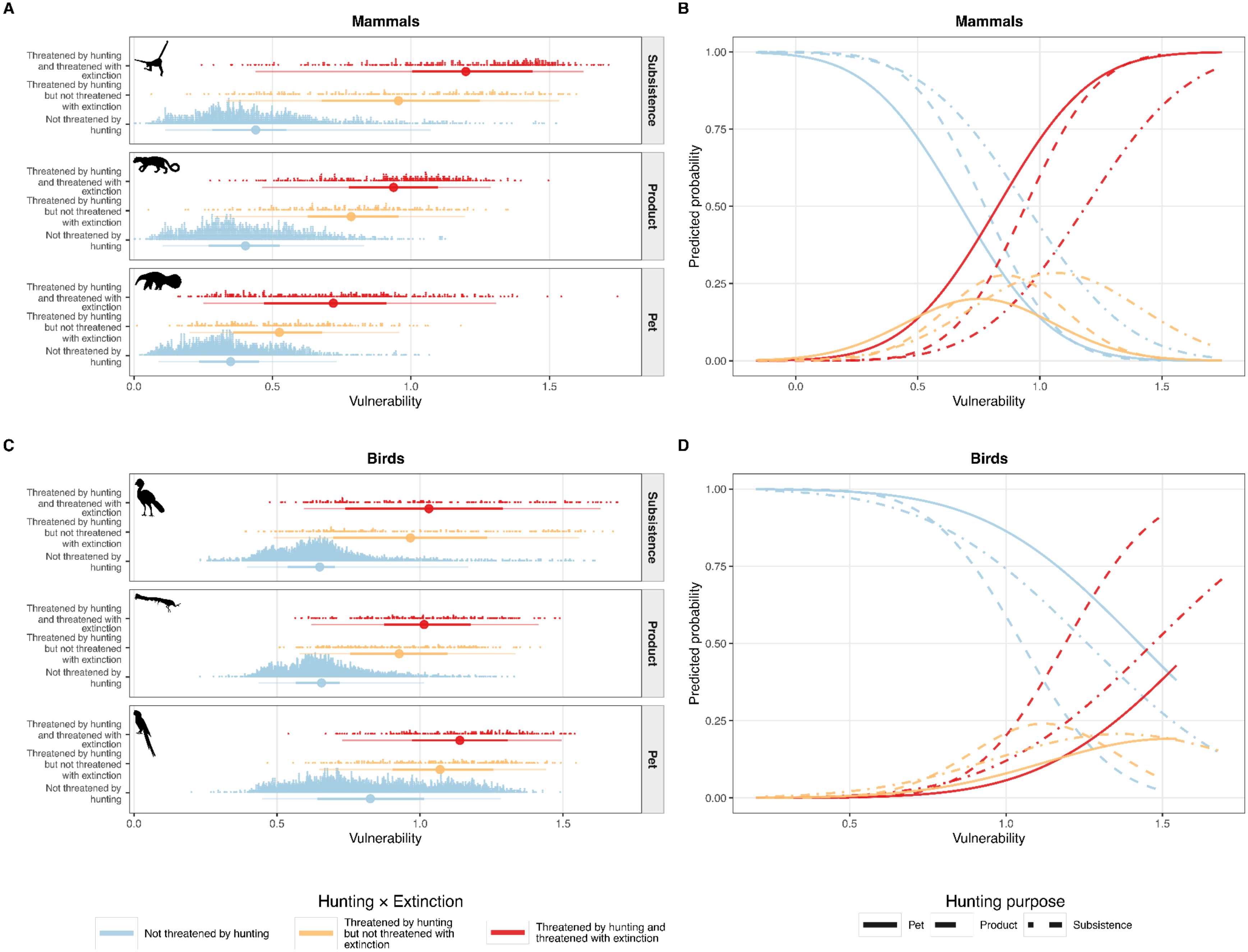
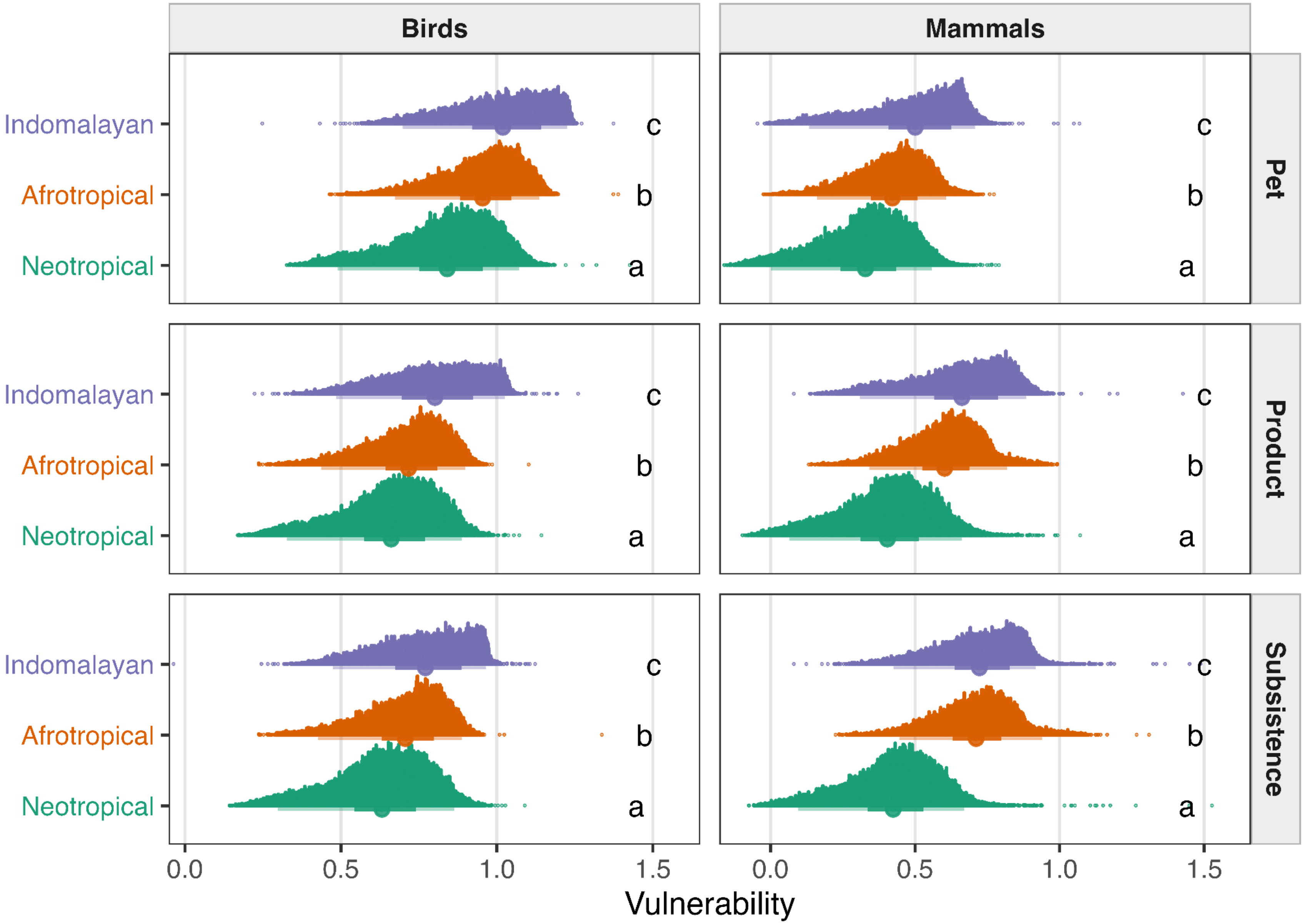

A
Mammals
Threatened by hunting and threatened with extinction
Threatened by hunting but not threatened with extinction
Not threatened by hunting
Subsistence
Product
Pet
0.0
0.5
1.0
1.5
Vulnerability
B
Mammals
Predicted probability
1.00
0.75
0.50
0.25
0.00
0.0
0.5
1.0
1.5
Vulnerability
C
Birds
Threatened by hunting and threatened with extinction
Threatened by hunting but not threatened with extinction
Not threatened by hunting
Subsistence
Product
Pet
0.0
0.5
1.0
1.5
Vulnerability
D
Birds
Predicted probability
1.00
0.75
0.50
0.25
0.00
0.5
1.0
1.5
Vulnerability
Hunting × Extinction
Not threatened by hunting
Threatened by hunting but not threatened with extinction
Threatened by hunting and threatened with extinction
Hunting purpose
Pet
Product
Subsistence

Figure 3. Species-level Vulnerability in tropical birds and mammals.

Species are color-coded by IUCN hunting and global extinction risk status: red indicates species assessed as threatened by hunting and at risk of extinction (listed as Vulnerable, Endangered, or Critically Endangered); yellow indicates species threatened by hunting but not at risk of extinction (Least Concern, Near Threatened or Data Deficient); and blue indicates species not threatened by hunting. Panels A and C show the distribution of species-level Vulnerability for tropical mammals and birds, respectively. Species-level Vulnerability is computed as the mean Vulnerability score across all 20 × 20 km spatial units within each species' range. Dot plots depict the distribution of scores for each IUCN hunting threat category (defined by the combination of hunting threat and extinction risk), ordered from least to most threatened. Thick colored bars show the 50% interval and thin bars the 95% interval around the mean, computed per threat category within each hunting purpose (Pet, Product, Subsistence). Panels B and D illustrate the relationship between species vulnerability scores and the probability of assignment to each IUCN hunting threat category (Hunting × Extinction). Fitted lines are derived from ordinal regression models (IUCN hunting threat category ~ Vulnerability), run separately for each hunting purpose. In all models, slope estimates were significant based on likelihood ratio tests, indicating that species with lower vulnerability scores were more likely to be classified as not threatened by hunting, whereas higher scores increased the probability of being classified as threatened by hunting and at risk of extinction. Silhouettes were sourced from PhyloPic.org (T. Michael Keesey, 2025).


Birds
Mammals
Pet
Product
Subsistence
Indomalayan
Afrotropical
Neotropical
c
b
a
0.0
0.5
1.0
1.5
Vulnerability

901

Figure 4. Comparisons of assemblage-level Vulnerability across realms.

Each distribution represents assemblage-level Vulnerability per spatial unit, calculated as the average Vulnerability of all species occurring within each 20 × 20 km spatial unit. Thick colored bars show the 50% interval and thin bars the 95% interval around the mean, computed per threat category within each hunting purpose (Pet, Product, Subsistence). Comparisons were conducted separately for each taxon and hunting purpose using pairwise comparisons of least-squares means with Šidák correction. Letters show statistically distinct groups, ordered from lowest (a) to highest mean vulnerability (c); realms sharing the same letter do not differ significantly. White diamonds indicate mean values per realm, while boxplots show the median and interquartile range.

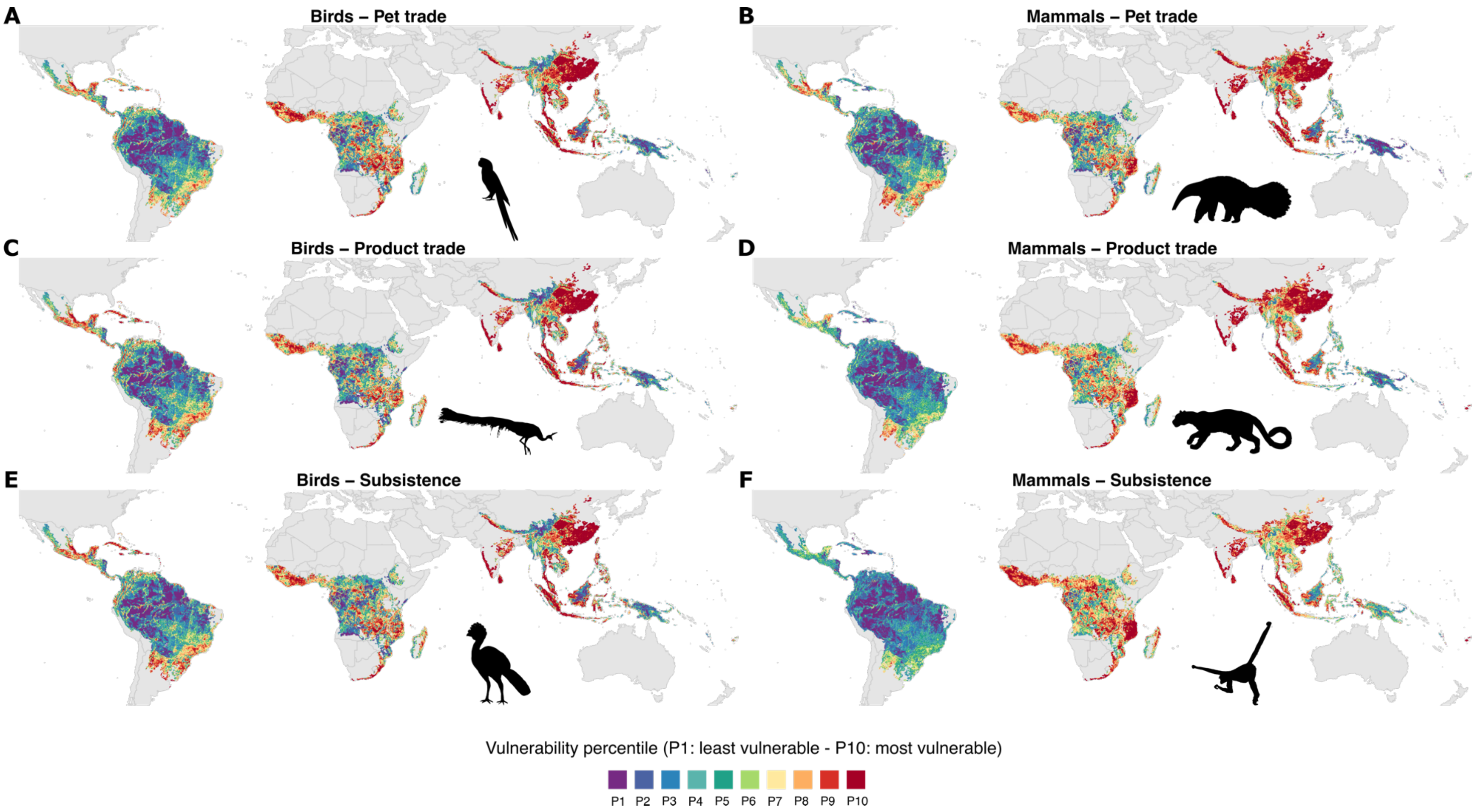


Figure 5. Spatial distribution of assemblage-level Vulnerability in tropical birds and mammals.

Panels A–C–E represent birds, and B–D–F represent mammals. Hunting purposes are divided as follows: A–B for pet trade, C–D for product trade, and E–F for subsistence hunting. Each map is divided into 10 equal-sized percentile classes (P1 to P10) since raw vulnerability scores are not directly interpretable, where P1 indicates the 10% of 20 × 20 km spatial units with the lowest assemblage-level Vulnerability and P10 the 10% with the highest assemblage-level Vulnerability Assemblage-level Vulnerability represents the mean Vulnerability score across all species occurring within a given 20 × 20 km spatial unit. Percentiles are calculated separately for each taxon–purpose combination to ensure comparability within each category. Percentile of assemblage-level Vulnerability is shown using a color gradient from purple (lowest vulnerability) to red (highest vulnerability), with green representing intermediate values. Silhouettes were sourced from PhyloPic.org (T. Michael Keesey, 2025).

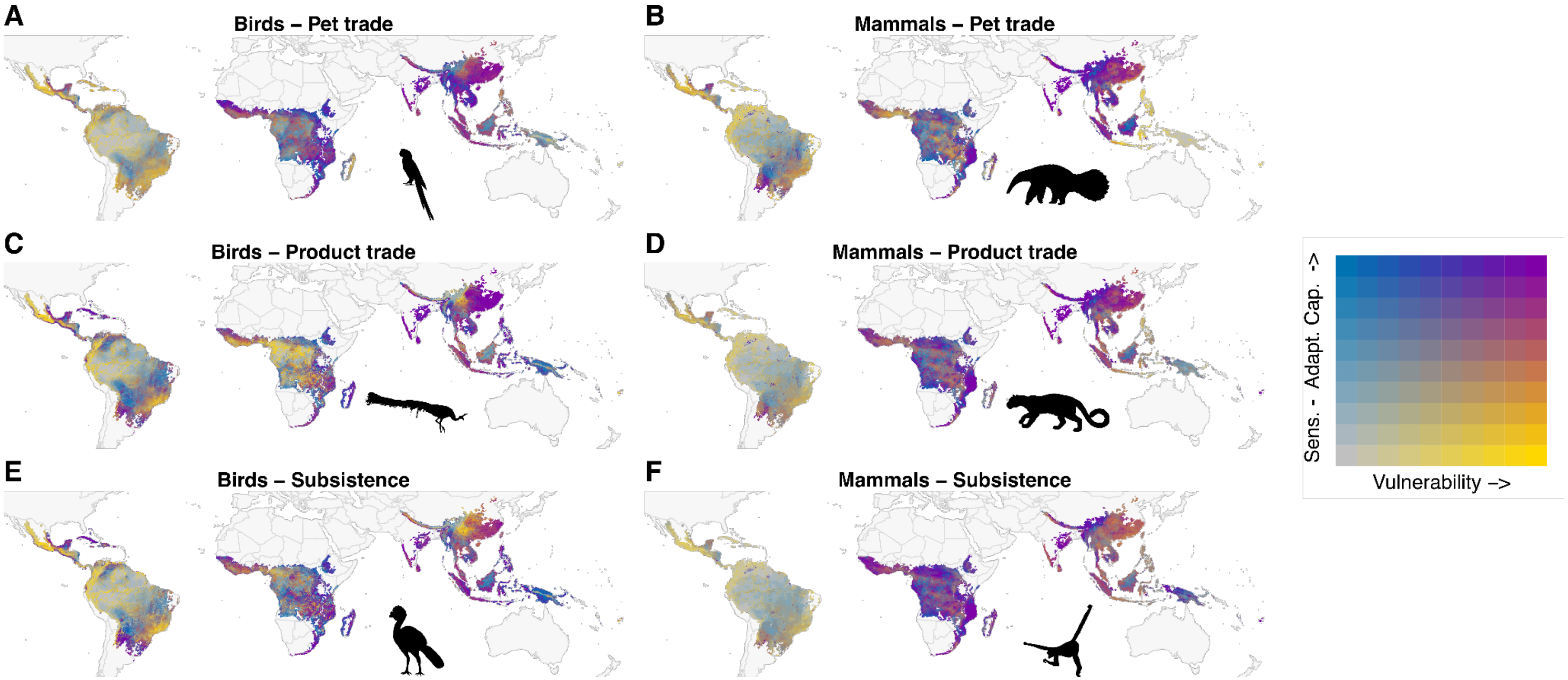


Figure 6. Bivariate maps of the spatial distribution of assemblage-level Sensitivity - Adaptive capacity and Vulnerability.

Panels A, C, and E represent birds, while panels B, D, and F correspond to mammals. Hunting purposes are categorized as follows: A–B for pet trade, C–D for product trade, and E–F for subsistence hunting. Each map is divided into 10 equal-sized percentile classes (P1 to P10), where P1 indicates the 10% of 20 × 20 km spatial units with the lowest assemblage-level scores and P10 the 10% with the highest assemblage-level scores for both Sensitivity - Adaptive capacity, i.e Intrinsic Vulnerability (IV), and Vulnerability. Percentiles are computed independently for each taxon–purpose combination to ensure comparability. The color gradient represents the joint variability of both scores. Grey areas indicate locations with both low Vulnerability and low IV, while purple areas reflect locations where both scores are high, indicating hotspots of concern. Yellow regions represent areas with high Vulnerability but low IV, suggesting high exposure but relatively low intrinsic vulnerability. In contrast, blue areas denote low Vulnerability and high IV, potentially identifying refugia where sensitive species are less exposed. Diagonal transitions from grey to purple reflect strong concordance between exposure and intrinsic susceptibility, whereas yellow and blue areas represent spatial mismatches between the two dimensions. Silhouettes were sourced from PhyloPic.org (T. Michael Keesey, 2025).

Supplementary Information

Supplementary Methods

2.2. Sensitivity

2.2.1. Probability of hunting

To assess the reliability of our modelling approach, we conducted additional validation analyses. Because our framework relied on bootstrapping, we obtained 100 fitted generalized linear mixed-effects models (GLMMs) for each combination of taxon and hunting purpose. Each model predicted species hunting status (1 = hunted, 0 = non-hunted) as a function of species traits included as fixed effects, with phylogeny modelled as a nested random effect (order/family). This structure accounts for shared evolutionary history, under the assumption that closely related species may share latent characteristics not explicitly captured by the selected traits. From the 100 fitted models, we extracted estimates of both fixed and random effects across bootstrap iterations. To evaluate the overall contribution of each trait, we applied a meta-analytic approach using the *rma()* function from the `metafor` R package [1]. Because all traits were standardized prior to modelling, effect sizes are directly comparable and provide an estimate of the relative importance of each trait in predicting whether a species is classified as hunted or non-hunted. Similarly, we extracted family-level random effects to assess the influence of phylogenetic structure in the models, allowing us to evaluate whether residual variation in hunting status was associated with taxonomic relatedness beyond the included trait predictors.

3.3. Robustness analysis

To assess the influence of our weighting scheme on species-level Sensitivity and Adaptive capacity scores, we compared the reference model to a range of alternative weighting scenarios. For Sensitivity, we tested different combinations of weights applied to the components (e.g., probability of being hunted and trade scale) for both pet and product trade, keeping the sum of the weights constant at 2. Specifically, we varied the weight of each component (A and B) from 0 to 2 in steps of 0.3, with the constraint B = 2 – A. Subsistence hunting was excluded from this analysis, as it lacks a trade scale component. For Adaptive capacity, we explored weighting schemes using trait data, maintaining total weights of 10 for birds (four traits) and 15 for mammals (five traits). We varied the individual weights (A–D or A–E) from 1 to 5 in steps of 1 and generated all possible combinations that respected the total sum constraint. For each weighting configuration, we recalculated the combined Sensitivity - Adaptive capacity score across species and compared it to the reference score using Spearman correlation coefficients. To quantify how variation in individual weightings affected similarity to the reference model, we ran linear models using *lm()* with difference in weight values between reference and tested scenario as predictors of the correlation outcome. The resulting regression coefficients indicated which trait weights had the strongest impact on the final scores, and whether increasing a weight made the alternative scenario consistent with the reference.

Supplementary Results

3. Sensitivity and Adaptive capacity of tropical birds and mammals

Our mixed models on the likelihood of birds and mammals being hunted showed good predictive performance across all purposes, with conditional R^2 values (mean ± SD) ranging from 0.50 ± 0.01 to 0.74 ± 0.01 (Fig. S6). We observed high variability in the predicted likelihood of species being hunted, depending on both taxonomic group and hunting type. Birds were most likely to be hunted for the pet trade (0.40 ± 0.29) than mammals (0.11 ± 0.21); whereas mammals were particularly harvested for the product trade (0.30 ± 0.37) and for subsistence (0.24 ± 0.32). The likelihood of birds being hunted for product trade (0.19 ± 0.25) or subsistence (0.12 ± 0.19) was considerably lower (Fig. S7). Phylogeny played a more important role in modeling the likelihood of being hunted for mammals than for birds, with the proportion of variance explained by phylogeny ranging from 0.46 ± 0.033 to 0.82 ± 0.013 in mammals, compared to 0.14 ± 0.021 to 0.28 ± 0.032 in birds (Fig S6).

When assessing the geographic scale of trade for each species, i.e., whether a species was traded for subsistence purposes and/or traded nationally and/or internationally. and for how many ‘end uses’ (only 1 for pets, and up to 16 for products for birds and mammals), we found that mammals are generally traded as products across for more end uses and broader spatial scales than birds (mean absolute trade score = 0.89 ± 2.39 for mammals vs. 0.46 ± 1.28 for birds).

When assessing the geographic scale and purpose of trade for each species—including whether species are used for subsistence and/or traded at national and/or international levels, and the number of end uses (only 1 for pets, and up to 16 for products for birds and mammals)—we found that mammals are generally traded for a wider range of products and across broader spatial scales than birds. On average, mammals showed higher trade scores than birds (mean ± SD: 0.89 ± 2.39 vs. 0.46 ± 1.28, respectively). In contrast, birds were traded more extensively as pets (1.15 ± 1.50, i.e. nationally and internationally) than mammals (0.13 ± 0.65, i.e. mostly locally). The maximum trade score for pet trade was 6 for both birds and mammals, indicating trade across all geographical scales. For product trade, the highest score reached was 26 for mammals (*Acinonyx jubatus*) and 12 for birds (*Pavo muticus*). After min-max standardization, bird pet trade showed the highest mean value (0.19 ± 0.25), followed by product trade for birds (0.04 ± 0.11) and mammals (0.03 ± 0.1), which were not statistically different. Mammal pet trade exhibited the lowest standardized value (0.02 ± 0.11) (Fig. S8).

Species Sensitivity (ranging from 0 to 1) and adaptive capacity were combined into a single composite metric of Intrinsic Vulnerability (IV) to hunting, calculated as IV = S - AC. Adaptive capacity was defined such that higher values (closer to 0) indicate lower capacity to cope with hunting, whereas more negative values indicate greater adaptive capacity. Adaptive capacity ranged from –0.69 (*Hirundo rustica*) to –0.015 (*Neomorphus geoffroyi*) for birds (mean ± SD: –0.13 ± 0.06), and from –0.64 (*Mustela nivalis*) to 0.005 (*Elephas maximus*) for mammals (mean ± SD: –0.30 ± 0.11). For both mammals and birds, species not threatened by hunting exhibited significantly lower IV scores than those identified as threatened by hunting or threatened by hunting and at risk of extinction (extinction risk: Vulnerable, Endangered or Critically Endangered according to the IUCN RedList, Fig. S9). We did not observe consistent significant differences in intrinsic vulnerability between species threatened by hunting and at risk of extinction and those threatened by hunting but not currently at risk, with two exceptions, mammals targeted by the pet trade and birds hunted for subsistence, for which non–globally threatened species exhibited higher IV (Fig. S9).

Body mass was positively correlated with hunting status across both taxa and all hunting purposes and consistently showed the strongest effect (Fig. S10). Population density was positively associated with hunting status in birds for pet trade and subsistence hunting, but negatively associated in mammals. For birds, this positive relationship may reflect the social behavior of species targeted for the pet trade and subsistence, where locally abundant and easily captured species are preferentially hunted. The negative relationship observed in mammals was unexpected and may reflect unmeasured traits associated with hunting preference—such as meat quality, behavioral characteristics desirable for the pet trade, or aesthetic features—that could be negatively correlated with density. In birds, tail length and color elaboration were positively correlated with hunting status for both pet and product trade, consistent with the hypothesis that visually conspicuous traits increase desirability. Beak size was negatively associated with pet trade, possibly reflecting the targeting of smaller, vocal passerines, although the absence of a significant positive effect for product trade was contrary to expectations. In mammals, brain mass (controlled for body mass) was positively associated with hunting status for the pet trade, consistent with the idea that relative brain size may act as a proxy for perceived intelligence, a trait valued in traded species. The weaker effect observed for product trade may reflect selective targeting of specific taxa, such as large carnivores, for products.

Phylogenetic effects across taxa and hunting purposes reflected biologically coherent patterns. For mammals, lemurs were predicted to be particularly targeted for subsistence hunting, whereas felids showed lower predicted probabilities (Fig. S11). Similarly, in the pet trade models, primates were more likely to be classified as hunted, while rodents showed lower probabilities (Fig. S12). For product trade, lemurs, civets, and rhinoceroses exhibited higher predicted hunting probabilities than rodents (Fig. S13). For birds, galliform species were more likely to be targeted for subsistence hunting than passerines (Fig. S14). In the pet trade models, colorful passerines, raptors, and parrots showed higher predicted hunting probabilities than nocturnal or crepuscular species and dull-colored passerines (Fig. S15). For product trade, hummingbirds, galliformes, and hornbills were more frequently predicted as hunted compared with small, dull-colored passerines (Fig. S16).

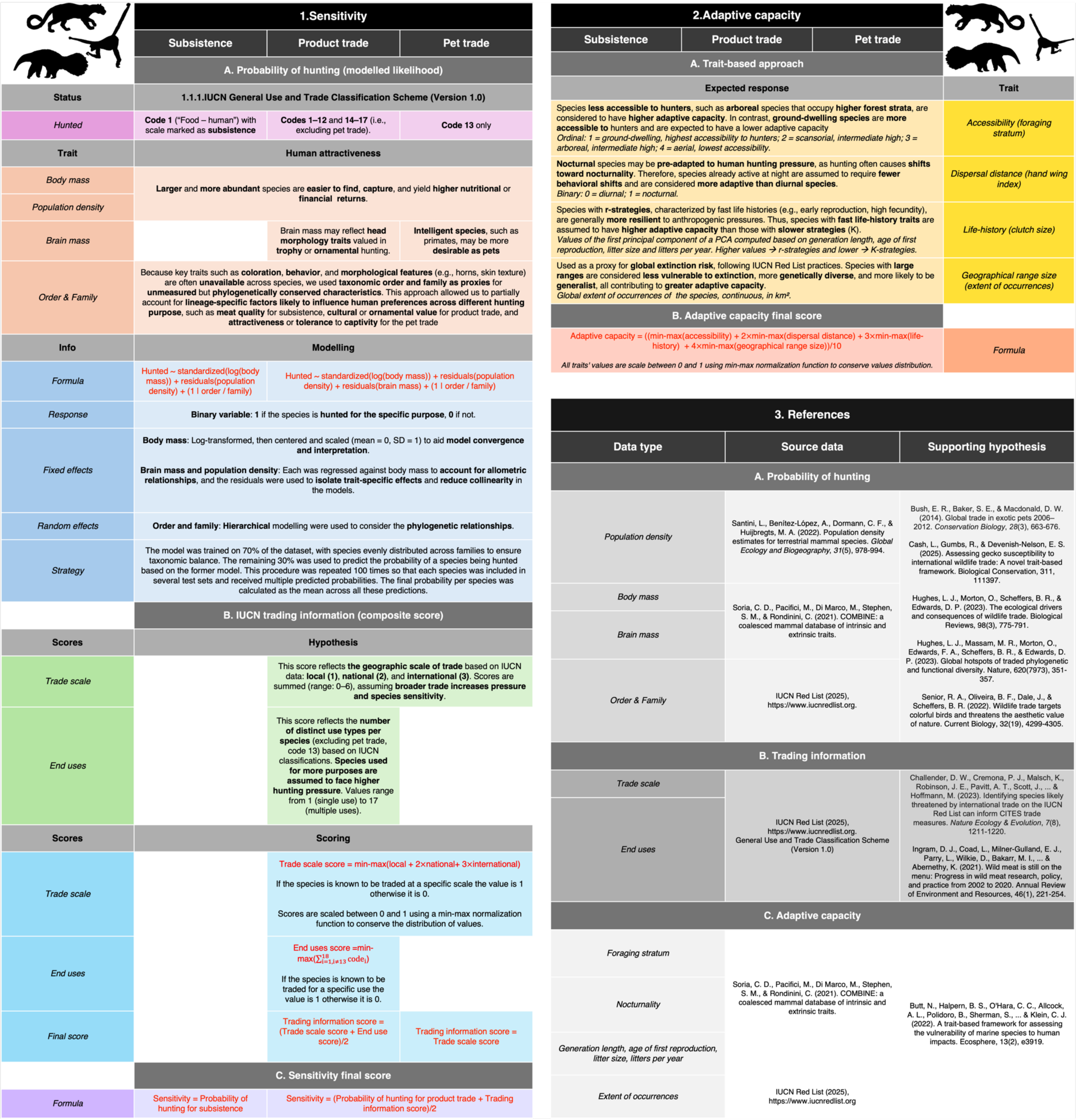
4.Result robustness

Sensitivity and Adaptive capacity, both combined into the final Vulnerability score, were non-spatialized components computed at the species level using a custom scoring system based on a set of predefined assumptions. These scoring choices directly influenced the distribution of Vulnerability values and species rankings across taxa and hunting purposes. To assess the robustness of our framework, we compared the reference scoring configuration to several alternatives. These included varying the weights assigned to (1) hunting probability, (2) trade scale, and (3) traits contributing to adaptive capacity. Overall, species rankings based on the composite score (Sensitivity - Adaptive capacity) remained relatively stable across alternative scenarios. Spearman correlation coefficients ranged from 0.85 ± 0.10 (pet trade), 0.85 ± 0.15 (product trade), and 0.86±0.24 (subsistence) for mammals, and from 0.95 ± 0.053 (pet), 0.92 ± 0.078 (product), and 0.89 ± 0.18 (subsistence) for birds (Fig. S17). Among all tested modifications, changing the weight of hunting probability had the strongest effect (Fig. S18). For mammals, reducing its weight relative to trade scale decreased correlation with the reference score from 0.99 (SE = 0.0057) at maximum weight to 0.75 (SE = 0.0052) at minimum weight. For birds, the drop was similar: from 1.01 (SE = 0.0028) to 0.91 (SE = 0.0030) (Fig. S18). Trait weightings also influenced species rankings, though to a lesser extent. In birds, adjusting the weight of primary lifestyle traits reduced the Spearman correlation of vulnerability rankings from 0.98 to 0.91 (SE = 0.0027 in both cases). In mammals, trait weighting had minimal impact on species rankings, indicating greater stability in the vulnerability score. The weighting of trade scale, set in the reference model as international = 3, national = 2, and local = 1, was particularly important for ranking bird species in the pet trade. Apart from one alternative weighting (local = 2, national = 1, international = 3), which reached a Spearman correlation of 1.00 with the reference model, all other combinations resulted in lower correlations, ranging from 0.21 to 0.41. In contrast, changes in trade scale weights had minimal effect on Vulnerability rankings for mammals (in both pet and product trade) and for birds in the product trade category, with correlation coefficients consistently above 0.99.

Supplementary References

1. Viechtbauer, W. metafor: Meta-Analysis Package for R. (2025).

Supplementary Figures



	1.Sensitivity		
	Subsistence	**Product trade**	**Pet trade**
	A. Probability of hunting (modelled likelihood)		
Status	**1.1.1.IUCN General Use and Trade Classification Scheme (Version 1.0)**		
Hunted	**Code 1** ("Food – human") with scale marked as **subsistence**	**Codes 1–12** and **14–17** (i.e., excluding pet trade).	**Code 13** only
Trait	**Human attractiveness**		
Body mass	**Larger** and **more abundant** species are **easier to find**, **capture**, and yield **higher nutritional** or **financial returns**.		
Population density			
Brain mass		Brain mass may reflect **head morphology traits** valued in **trophy** or **ornamental** hunting.	**Intelligent species**, such as primates, may be more **desirable as pets**
Order & Family	Because key traits such as **coloration**, **behavior**, and **morphological features** (e.g., horns, skin texture) are often **unavailable** across species, we used **taxonomic order and family as proxies** for **unmeasured** but **phylogenetically conserved characteristics**. This approach allowed us to partially account for **lineage-specific factors likely to influence human preferences across different hunting purpose**, such as **meat quality** for subsistence, **cultural** or **ornamental value** for product trade, and **attractiveness** or **tolerance** to **captivity** for the pet trade		
Info	**Modelling**		
Formula	Hunted ~ standardized(log(body mass)) + residuals(population density) + (1 I order / family)	Hunted ~ standardized(log(body mass)) + residuals(population density) + residuals(brain mass) + (1 I order / family)	
Response	**Binary variable**: **1** if the species is **hunted for the specific purpose**, **0** if not.		
Fixed effects	**Body mass**: Log-transformed, then centered and scaled (mean = 0, SD = 1) to aid **model convergence and interpretation**. **Brain mass and population density**: Each was regressed against body mass to **account for allometric relationships**, and the residuals were used to **isolate trait-specific effects** and **reduce collinearity** in the models.		
Random effects	**Order and family**: **Hierarchical** modelling were used to consider the **phylogenetic relationships**.		
Strategy	The model was trained on 70% of the dataset, with species evenly distributed across families to ensure taxonomic balance. The remaining 30% was used to predict the probability of a species being hunted based on the former model. This procedure was repeated 100 times so that each species was included in several test sets and received multiple predicted probabilities. The final probability per species was calculated as the mean across all these predictions.		
	B. IUCN trading information (composite score)		
Scores	**Hypothesis**		
Trade scale		This score reflects **the geographic scale of trade** based on IUCN data: **local (1)**, **national (2)**, and **international (3)**. Scores are summed (range: 0–6), assuming **broader trade increases pressure and species sensitivity**.	
End uses		This score reflects the **number of distinct use types per species** (excluding pet trade, code 13) based on IUCN classifications. **Species used for more purposes are assumed to face higher hunting pressure**. Values range from 1 (single use) to 17 (multiple uses).	
Scores	**Scoring**		
Trade scale		Trade scale score = min-max(local + 2×national+ 3×international) If the species is known to be traded at a specific scale the value is 1 otherwise it is 0. Scores are scaled between 0 and 1 using a min-max normalization function to conserve the distribution of values.	
End uses		End uses score =min-max($\sum_{i=1,i\neq13}^{18} \text{code}_i$) If the species is known to be traded for a specific use the value is 1 otherwise it is 0.	
Final score		Trading information score = (Trade scale score + End use score)/2	Trading information score = Trade scale score
	C. Sensitivity final score		
Formula	Sensitivity = Probability of hunting for subsistence	Sensitivity = (Probability of hunting for product trade + Trading information score)/2	

2.Adaptive capacity			
Subsistence	**Product trade**	**Pet trade**	
A. Trait-based approach			
Expected response			**Trait**
Species **less accessible to hunters**, such as **arboreal** species that occupy **higher forest strata**, are considered to have **higher adaptive capacity**. In contrast, **ground-dwelling species** are **more accessible to** hunters and are expected to have a lower adaptive capacity *Ordinal: 1 = ground-dwelling, highest accessibility to hunters; 2 = scansorial, intermediate high; 3 = arboreal, intermediate high; 4 = aerial, lowest accessibility.*			*Accessibility (foraging stratum)*
Nocturnal species may be **pre-adapted to human hunting pressure**, as hunting often causes **shifts toward nocturnality**. Therefore, species already active at night are assumed to require **fewer behavioral shifts** and are considered **more adaptive than diurnal species**. *Binary: 0 = diurnal; 1 = nocturnal.*			*Dispersal distance (hand wing index)*
Species with **r-strategies**, characterized by fast life histories (e.g., early reproduction, high fecundity), are generally **more resilient** to anthropogenic pressures. Thus, species with **fast life-history traits** are assumed to have **higher adaptive capacity** than those with **slower strategies** (K). *Values of the first principal component of a PCA computed based on generation length, age of first reproduction, litter size and litters per year. Higher values → r-strategies and lower → K-strategies.*			*Life-history (clutch size)*
Used as a proxy for **global extinction risk**, following IUCN Red List practices. Species with **large ranges** are considered **less vulnerable to extinction**, more **genetically diverse**, and more likely to be **generalist**, all contributing to **greater adaptive capacity**. *Global extent of occurrences of the species, continuous, in km².*			*Geographical range size (extent of occurrences)*
B. Adaptive capacity final score			
Adaptive capacity = ((min-max(accessibility) + 2×min-max(dispersal distance) + 3×min-max(life-history) + 4×min-max(geographical range size))/10 *All traits' values are scale between 0 and 1 using min-max normalization function to conserve values distribution.*			*Formula*

3. References		
Data type	**Source data**	**Supporting hypothesis**
A. Probability of hunting		
Population density	Santini, L., Benítez-López, A., Dormann, C. F., & Huijbregts, M. A. (2022). Population density estimates for terrestrial mammal species. *Global Ecology and Biogeography*, *31*(5), 978-994.	Bush, E. R., Baker, S. E., & Macdonald, D. W. (2014). Global trade in exotic pets 2006–2012. *Conservation Biology*, *28*(3), 663-676. Cash, L., Gumbs, R., & Devenish-Nelson, E. S. (2025). Assessing gecko susceptibility to international wildlife trade: A novel trait-based framework. Biological Conservation, 311, 111397. Hughes, L. J., Morton, O., Scheffers, B. R., & Edwards, D. P. (2023). The ecological drivers and consequences of wildlife trade. Biological Reviews, 98(3), 775-791. Hughes, L. J., Massam, M. R., Morton, O., Edwards, F. A., Scheffers, B. R., & Edwards, D. P. (2023). Global hotspots of traded phylogenetic and functional diversity. Nature, 620(7973), 351-357. Senior, R. A., Oliveira, B. F., Dale, J., & Scheffers, B. R. (2022). Wildlife trade targets colorful birds and threatens the aesthetic value of nature. Current Biology, 32(19), 4299-4305.
Body mass	Soria, C. D., Pacifici, M., Di Marco, M., Stephen, S. M., & Rondinini, C. (2021). COMBINE: a coalesced mammal database of intrinsic and extrinsic traits.	
Brain mass		
Order & Family	IUCN Red List (2025), https://www.iucnredlist.org.	
B. Trading information		
Trade scale	IUCN Red List (2025), https://www.iucnredlist.org. General Use and Trade Classification Scheme (Version 1.0)	Challender, D. W., Cremona, P. J., Malsch, K., Robinson, J. E., Pavitt, A. T., Scott, J., ... & Hoffmann, M. (2023). Identifying species likely threatened by international trade on the IUCN Red List can inform CITES trade measures. *Nature Ecology & Evolution*, *7*(8), 1211-1220. Ingram, D. J., Coad, L., Milner-Gulland, E. J., Parry, L., Wilkie, D., Bakarr, M. I., ... & Abernethy, K. (2021). Wild meat is still on the menu: Progress in wild meat research, policy, and practice from 2002 to 2020. Annual Review of Environment and Resources, 46(1), 221-254.
End uses		
C. Adaptive capacity		
Foraging stratum	Soria, C. D., Pacifici, M., Di Marco, M., Stephen, S. M., & Rondinini, C. (2021). COMBINE: a coalesced mammal database of intrinsic and extrinsic traits.	Butt, N., Halpern, B. S., O'Hara, C. C., Allcock, A. L., Polidoro, B., Sherman, S., ... & Klein, C. J. (2022). A trait-based framework for assessing the vulnerability of marine species to human impacts. Ecosphere, 13(2), e3919.
Nocturnality		
Generation length, age of first reproduction, litter size, litters per year		
Extent of occurrences	IUCN Red List (2025), https://www.iucnredlist.org	

Figure S1. Species-level Sensitivity and Adaptive capacity in mammals.

This figure provides a detailed description of the traits used to compute species-level Sensitivity and Adaptive capacity for mammals, including the rationale for trait selection and the associated references.

	**1.Sensitivity**		
	Subsistence	**Product trade**	**Pet trade**
	A. Probability of hunting (modelled likelihood)		
Status	**1.1.1.IUCN General Use and Trade Classification Scheme (Version 1.0)**		
Hunted	**Code 1** (“Food – human”) with scale marked as **subsistence**	**Codes 1–12** and **14–17** (i.e., excluding pet trade).	**Code 13** only
Trait	**Human attractiveness**		
Body mass	**Larger** and **more abundant** species are **easier to find**, **capture**, and yield **higher nutritional** or **financial returns**.		
Population density			
Color elaboration		**Color elaboration**, **beak length**, and **tail length** were included as **proxies** for species **attractiveness**, assuming that more distinctive morphological traits (e.g., vivid colors, long ornamentation) **increase desirability** for non-food uses such as handicrafts, jewelry, or display but also as pet and reflect **culturally valued features**.	
Beak length			
Tail length			
Order & Family	Because **key traits** are often **unavailable across species**, we used **taxonomic order and family** as **proxies** for **unmeasured but phylogenetically conserved characteristics**. This allowed us to partially capture **lineage-specific factors likely influencing human preferences across hunting purposes**, such as **meat quality** for subsistence, **cultural** or **ornamental value** for product trade, and **attractiveness** or **tolerance to captivity** for the pet trade. We also assumed that certain groups, like **parrots or songbirds**, may be preferentially targeted in ways **not fully explained by available morphological traits**.		
Info	**Modelling**		
Formula	Hunted ~ standardized(log(body mass)) + residuals(population density) + (1 I order / family)	Hunted ~ standardized(log(body mass)) + residuals(population density) + elaboration + residuals(beak length) + residuals(tail length) + (1 I order / family)	
Response	**Binary variable**: **1** if the species is **hunted for the specific purpose**, **0** if not.		
Fixed effects	**Body mass**: Log-transformed, then centered and scaled (mean = 0, SD = 1) to aid **model convergence and interpretation**. **Beak length, tail length and population density**: Each was regressed against body mass to **account for allometric relationships**, and the residuals were used to **isolate trait-specific effects** and **reduce collinearity** in the models.		
Random effects	**Order and family**: **Hierarchical** modelling were used to consider the **phylogenetic relationships**.		
Strategy	The model was trained on 70% of the dataset, with species evenly distributed across families to ensure taxonomic balance. The remaining 30% was used to predict the probability of a species being hunted based on the former model. This procedure was repeated 100 times so that each species was included in several test sets and received multiple predicted probabilities. The final probability per species was calculated as the mean across all these predictions.		
	B. IUCN trading information (composite score)		
Scores	**Hypothesis**		
Trade scale		This score reflects **the geographic scale of trade** based on IUCN data: **local (1)**, **national (2)**, and **international (3)**. Scores are summed (range: 0–6), assuming **broader trade increases pressure and species sensitivity**.	
End uses		This score reflects the **number of distinct use types per species** (excluding pet trade, code 13) based on IUCN classifications. **Species used for more purposes are assumed to face higher hunting pressure**. Values range from 1 (single use) to 17 (multiple uses).	
Scores	**Scoring**		
Trade scale		Trade scale score = min-max(local + 2×national+ 3×international) If the species is known to be traded at a specific scale the value is 1 otherwise it is 0. Scores are scaled between 0 and 1 using a min-max normalization function to conserve the distribution of values.	
End uses		End uses score =min-max($\sum_{i=1,i\neq13}^{18} \mathrm{code}_i$) If the species is known to be traded for a specific use the value is 1 otherwise it is 0.	
Final score		Trading information score = (Trade scale score + End use score)/2	Trading information score = Trade scale score
	C. Sensitivity final score		
Formula	Sensitivity = Probability of hunting for subsistence	Sensitivity = (Probability of hunting for product trade + Trading information score)/2	

2.Adaptive capacity			
Subsistence	**Product trade**	**Pet trade**	
A. Trait-based approach			
Expected response			**Trait**
Species **less accessible to hunters**, such as **aerial** species or that occupy **higher forest strata**, are considered to have **higher adaptive capacity**. In contrast, **ground-dwelling** species are more vulnerable and thus **less adaptive**. *Ordinal: 1 = ground-dwelling, highest accessibility to hunters; 2 = insessorial, generalist or aquatic, intermediate; 3 = aerial, lowest accessibility.*			*Accessibility (Primary lifestyle)*
Species with **longer dispersal distances** are better able to **escape hunting hotspots** and **recolonize** areas when pressure decreases. As such, **greater dispersal capacity** is interpreted as **higher adaptive capacity**. We used the hand-wing index (HWI) a morphological proxy for dispersal ability, with higher values indicate better dispersion of species. *Continuous, in cm.*			*Nocturnality (diurnal or nocturnal)*
Species with **r-strategies**, characterized by fast life histories (e.g., early reproduction, high fecundity), are generally **more resilient** to anthropogenic pressures. Thus, species with **fast life-history traits** are assumed to have **higher adaptive capacity** than those with **slower strategies** (K). We used **clutch size** as a proxy for reproductive strategy, as it is the only widely available trait across species . *Continuous, average number of eggs per breeding attempt*			*Life-history (generation length, age of first reproduction, litter size, litters per year)*
Used as a proxy for **global extinction risk**, following IUCN Red List practices. Species with **large ranges** are considered **less vulnerable to extinction**, more **genetically diverse**, and more likely to be **generalist**, all contributing to **greater adaptive capacity**. *Global extent of occurrences of the species, continuous, in km².*			*Geographical range size (extent of occurrences)*
B. Adaptive capacity final score			
Adaptive capacity = ((min-max(accessibility) + 2×min-max(nocturnality) + 3×min-max(life-history) + 4×min-max(geographical range size))/10 *All traits' values are scale between 0 and 1 using min-max normalization function to conserve values distribution.*			*Formula*

3. References		
Data type	**Source data**	**Supporting hypothesis**
A. Probability of hunting		
Population density	Santini, L., Tobias, J. A., Callaghan, C., Gallego-Zamorano, J., & Benítez-López, A. (2023). Global patterns and predictors of avian population density. *Global Ecology and Biogeography*, *32*(7), 1189-1204.	Bush, E. R., Baker, S. E., & Macdonald, D. W. (2014). Global trade in exotic pets 2006–2012. *Conservation Biology*, *28*(3), 663-676. Cash, L., Gumbs, R., & Devenish-Nelson, E. S. (2025). Assessing gecko susceptibility to international wildlife trade: A novel trait-based framework. Biological Conservation, 311, 111397. Hughes, L. J., Morton, O., Scheffers, B. R., & Edwards, D. P. (2023). The ecological drivers and consequences of wildlife trade. Biological Reviews, 98(3), 775-791. Hughes, L. J., Massam, M. R., Morton, O., Edwards, F. A., Scheffers, B. R., & Edwards, D. P. (2023). Global hotspots of traded phylogenetic and functional diversity. Nature, 620(7973), 351-357. Senior, R. A., Oliveira, B. F., Dale, J., & Scheffers, B. R. (2022). Wildlife trade targets colorful birds and threatens the aesthetic value of nature. Current Biology, 32(19), 4299-4305.
Body mass	Tobias, J. A., Sheard, C., Pigot, A. L., Devenish, A. J., Yang, J., Sayol, F., ... & Schleuning, M. (2022). AVONET: morphological, ecological and geographical data for all birds. *Ecology letters*, *25*(3), 581-597.	
Beak length		
Tail length		
Elaboration	Santangeli, A., Haukka, A., Morris, W., Arkkila, S., Delhey, K., Kempenaers, B., ... & Mammola, S. (2023). What drives our aesthetic attraction to birds?. *npj Biodiversity*, *2*(1), 20.	
Order & Family	IUCN Red List (2025), https://www.iucnredlist.org.	
B. Trading information		
Trade scale	IUCN Red List (2025), https://www.iucnredlist.org. General Use and Trade Classification Scheme (Version 1.0)	Challender, D. W., Cremona, P. J., Malsch, K., Robinson, J. E., Pavitt, A. T., Scott, J., ... & Hoffmann, M. (2023). Identifying species likely threatened by international trade on the IUCN Red List can inform CITES trade measures. *Nature Ecology & Evolution*, *7*(8), 1211-1220. Ingram, D. J., Coad, L., Milner-Gulland, E. J., Parry, L., Wilkie, D., Bakarr, M. I., ... & Abernethy, K. (2021). Wild meat is still on the menu: Progress in wild meat research, policy, and practice from 2002 to 2020. Annual Review of Environment and Resources, 46(1), 221-254.
End uses		
C. Adaptive capacity		
Foraging stratum	Tobias, J. A., Sheard, C., Pigot, A. L., Devenish, A. J., Yang, J., Sayol, F., ... & Schleuning, M. (2022). AVONET: morphological, ecological and geographical data for all birds. *Ecology letters*, *25*(3), 581-597.	Butt, N., Halpern, B. S., O'Hara, C. C., Allcock, A. L., Polidoro, B., Sherman, S., ... & Klein, C. J. (2022). A trait-based framework for assessing the vulnerability of marine species to human impacts. Ecosphere, 13(2), e3919.
Dispersal distance		
Clutch size	Marino, C., Leclerc, C., & Bellard, C. (2022). Profiling insular vertebrates prone to biological invasions: What makes them vulnerable?. Global Change Biology, 28(3), 1077-1090.	
Extent of occurrences	IUCN Red List (2025), https://www.iucnredlist.org	

Figure S2. Species-level Sensitivity and Adaptive capacity in birds.

This figure provides a detailed description of the traits used to compute species-level Sensitivity and Adaptive capacity for birds, including the rationale for trait selection and the associated references.

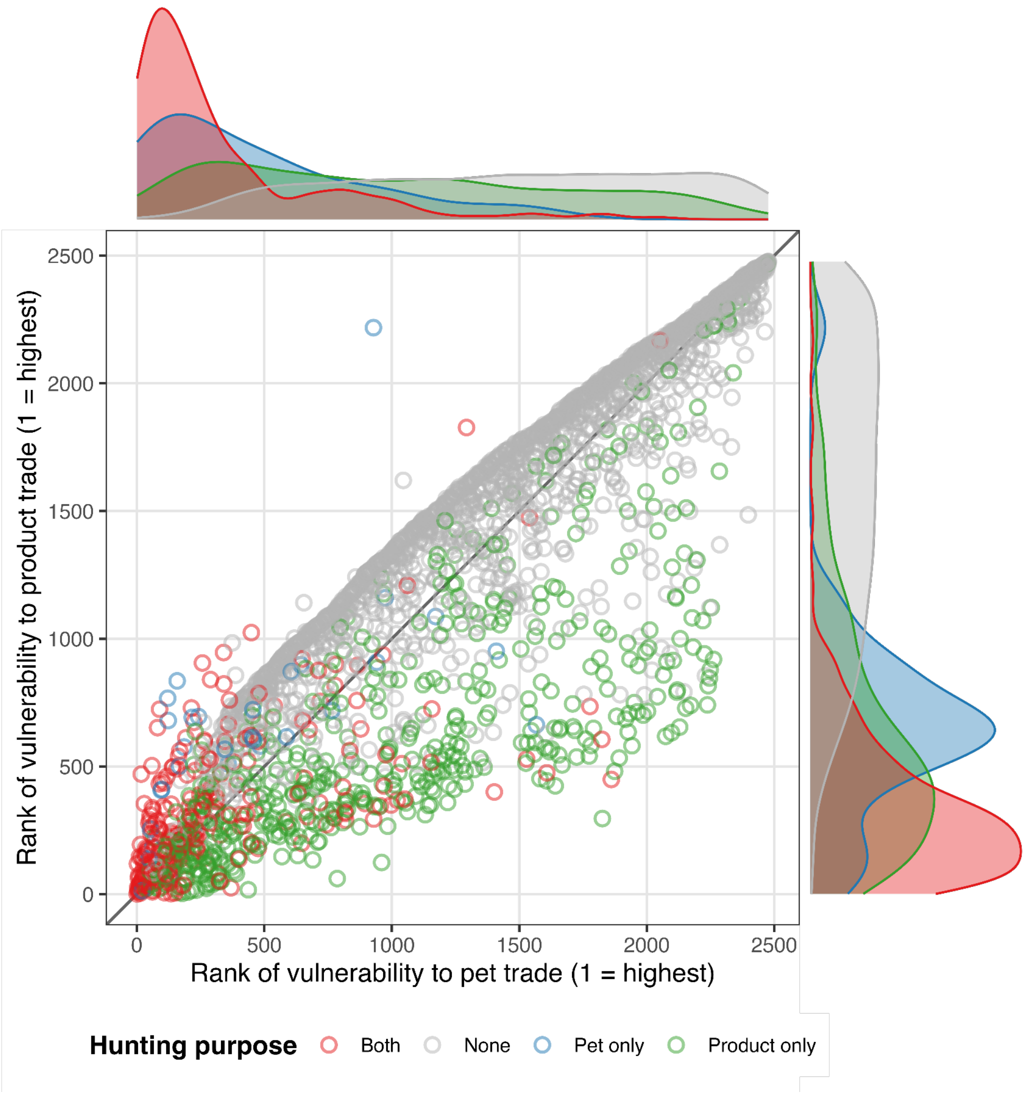


Figure S3. Distribution of vulnerability scores for tropical mammals hunted for pet and product trade, shown in relation to their hunting status.

Each point represents a species, positioned according to its rank in vulnerability for pet trade (x-axis) and product trade (y-axis), with lower values indicating higher vulnerability. Point colors reflect the hunting status of the species: whether it is hunted for pet trade, product trade, or both, or not hunted, based on our compiled database. The distributions along the x and y axes indicate the number of species per hunting category across vulnerability ranks.

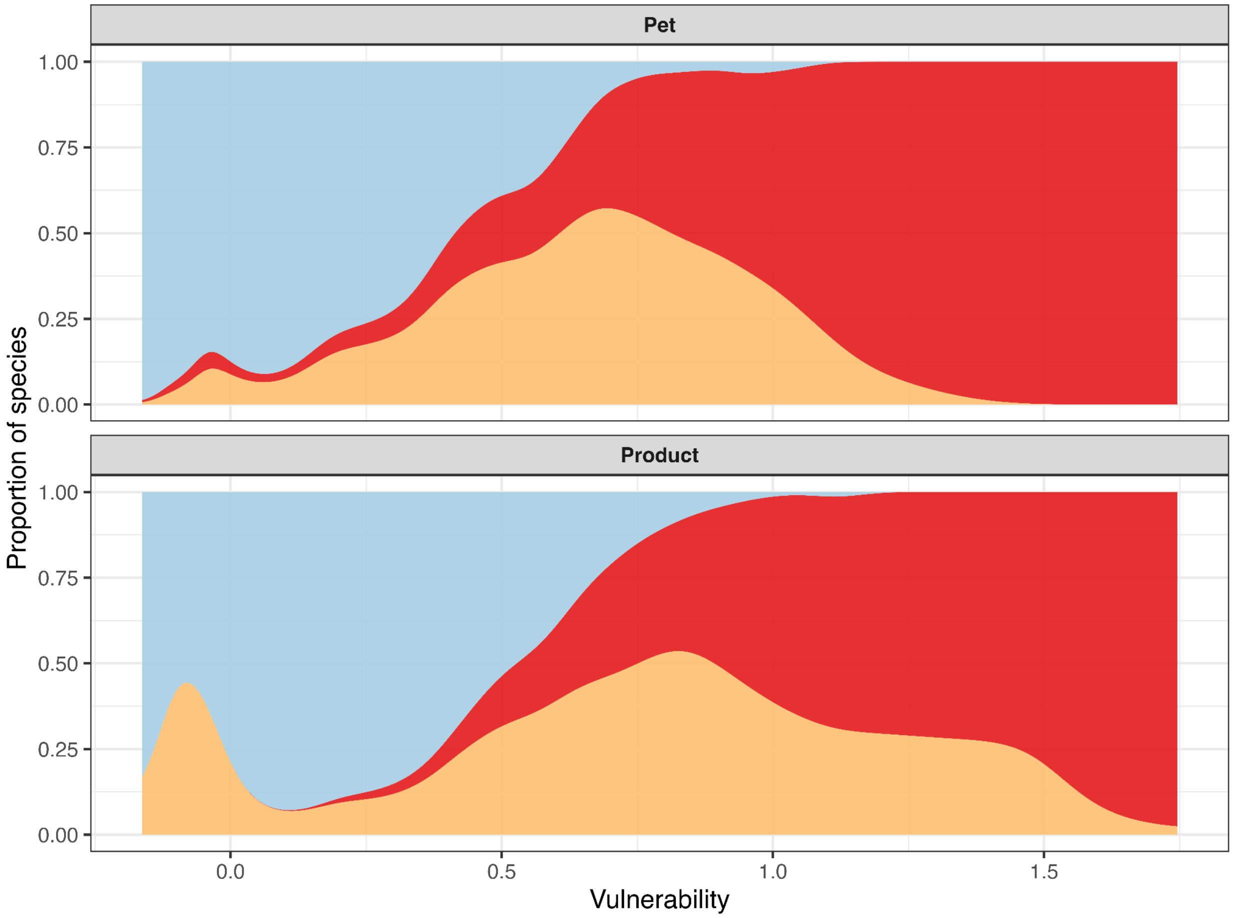


Figure S4. Proportion of IUCN hunting threat category according to species-level Vulnerability score for tropical mammals.

Each point represents a species, positioned according to its rank in vulnerability for pet trade (x-axis) and product trade (y-axis), with lower values indicating higher vulnerability. Point colors reflect the hunting status of the species: whether it is hunted for pet trade, product trade, or both, or not hunted, based on our compiled database. The distributions along the x and y axes indicate the number of species per hunting category across vulnerability ranks. Species assessed as threatened by hunting and threatened with extinction (i.e., listed as Vulnerable, Endangered, or Critically Endangered in the IUCN Red List) are shown in red. Species considered threatened by hunting but not classified as threatened with extinction (i.e., listed as Least Concern or Near Threatened) are shown in yellow. Species not assessed as threatened by hunting are shown in blue.

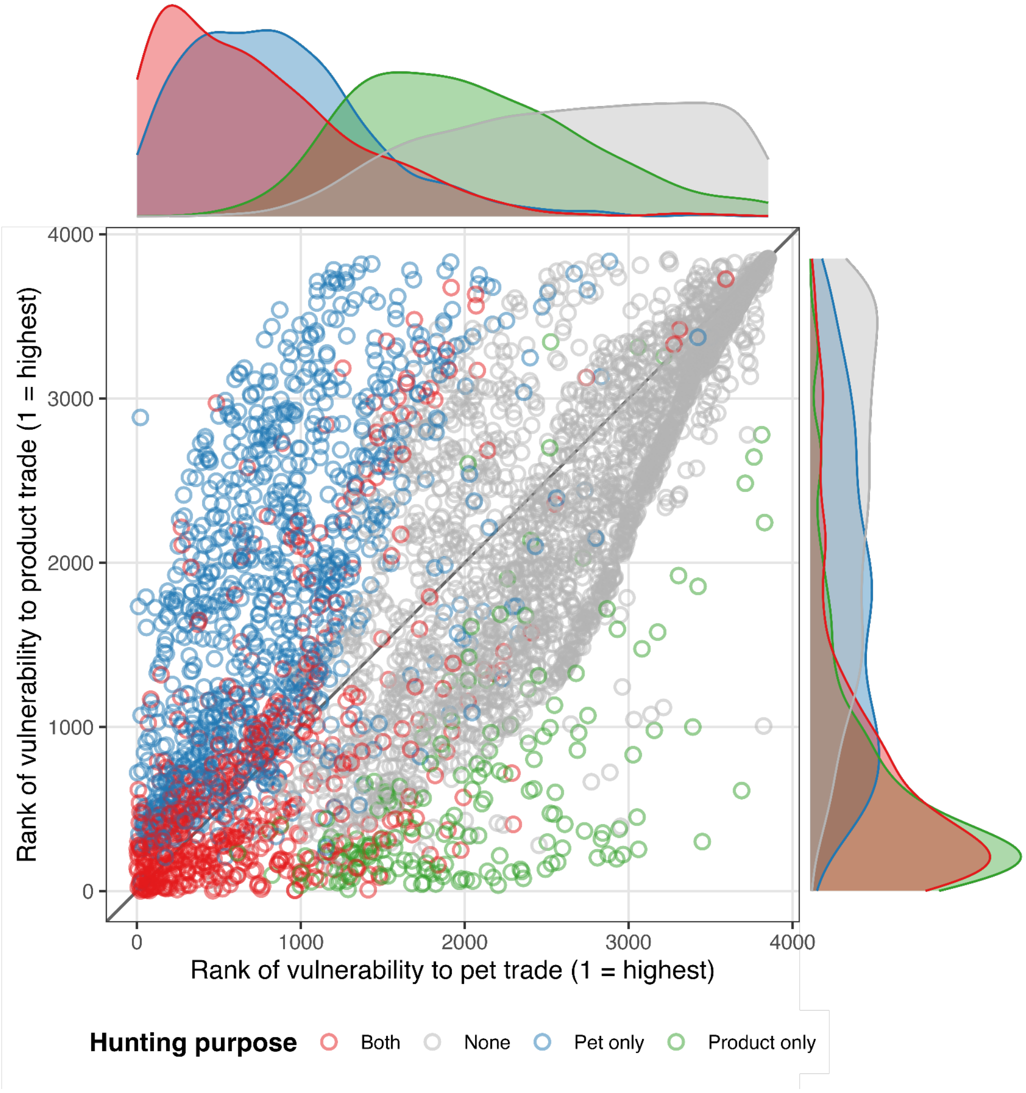


Figure S5. Distribution of vulnerability scores for tropical birds hunted for pet and product trade, shown in relation to their hunting status.

Each point represents a species, positioned according to its rank in vulnerability for pet trade (x-axis) and product trade (y-axis), with lower values indicating higher vulnerability. Point colors reflect the hunting status of the species: whether it is hunted for pet trade, product trade, or both, or not hunted, based on our compiled database. The distributions along the x and y axes indicate the number of species per hunting category across vulnerability ranks.

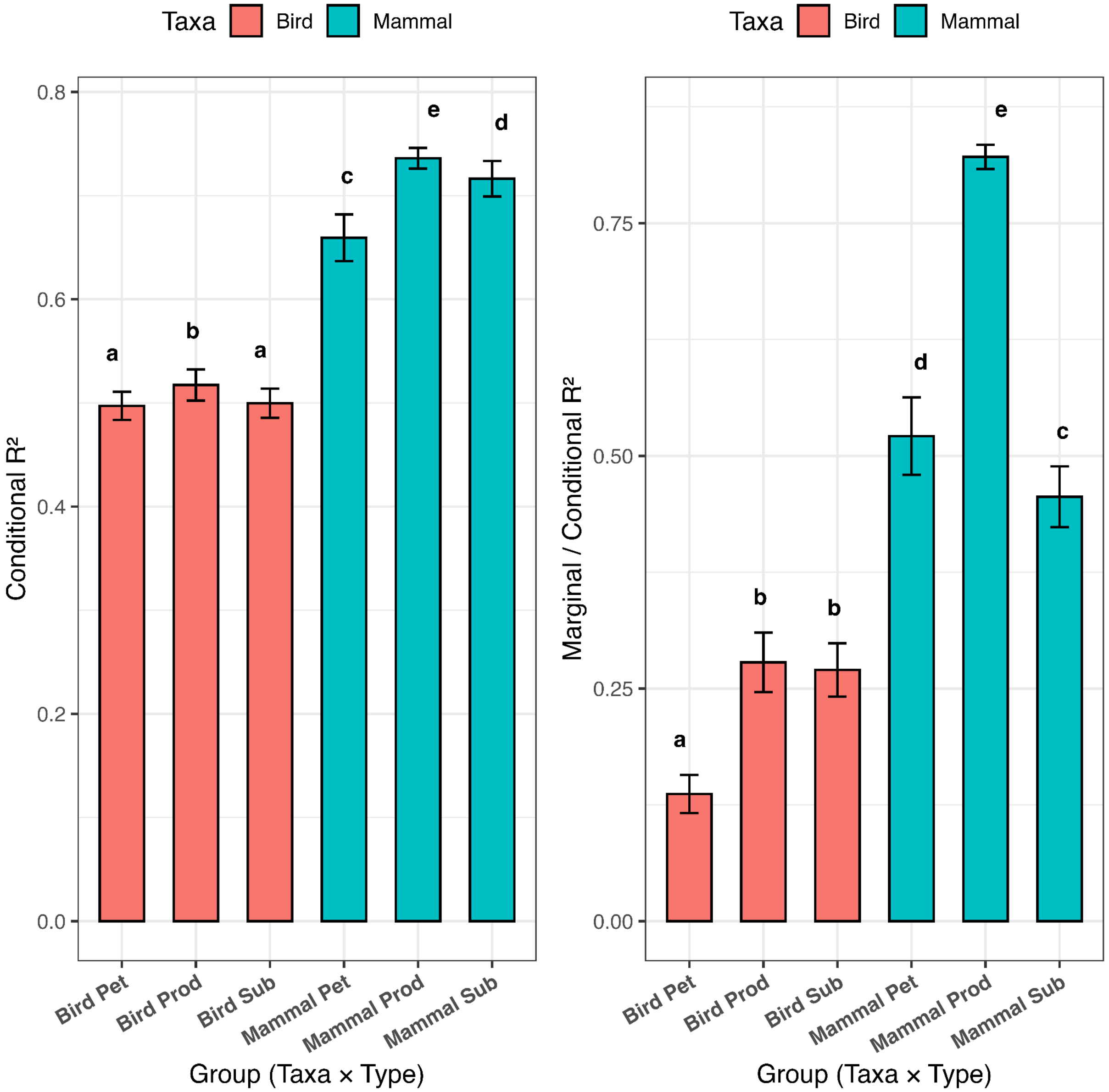


Figure S6. Goodness-of-fit of models predicting hunting likelihood from species traits and phylogeny.

The left panel displays the mean conditional R² of each binomial regression across 100 random subsets (each containing 70% of species), shown as bars, with error bars representing the associated standard deviations. The right panel shows the ratio of marginal to conditional R², indicating the proportion of variance explained by phylogeny in each model. Each bar corresponds to a different hunting purpose (pet, product, subsistence), with birds shown in red and mammals in blue.

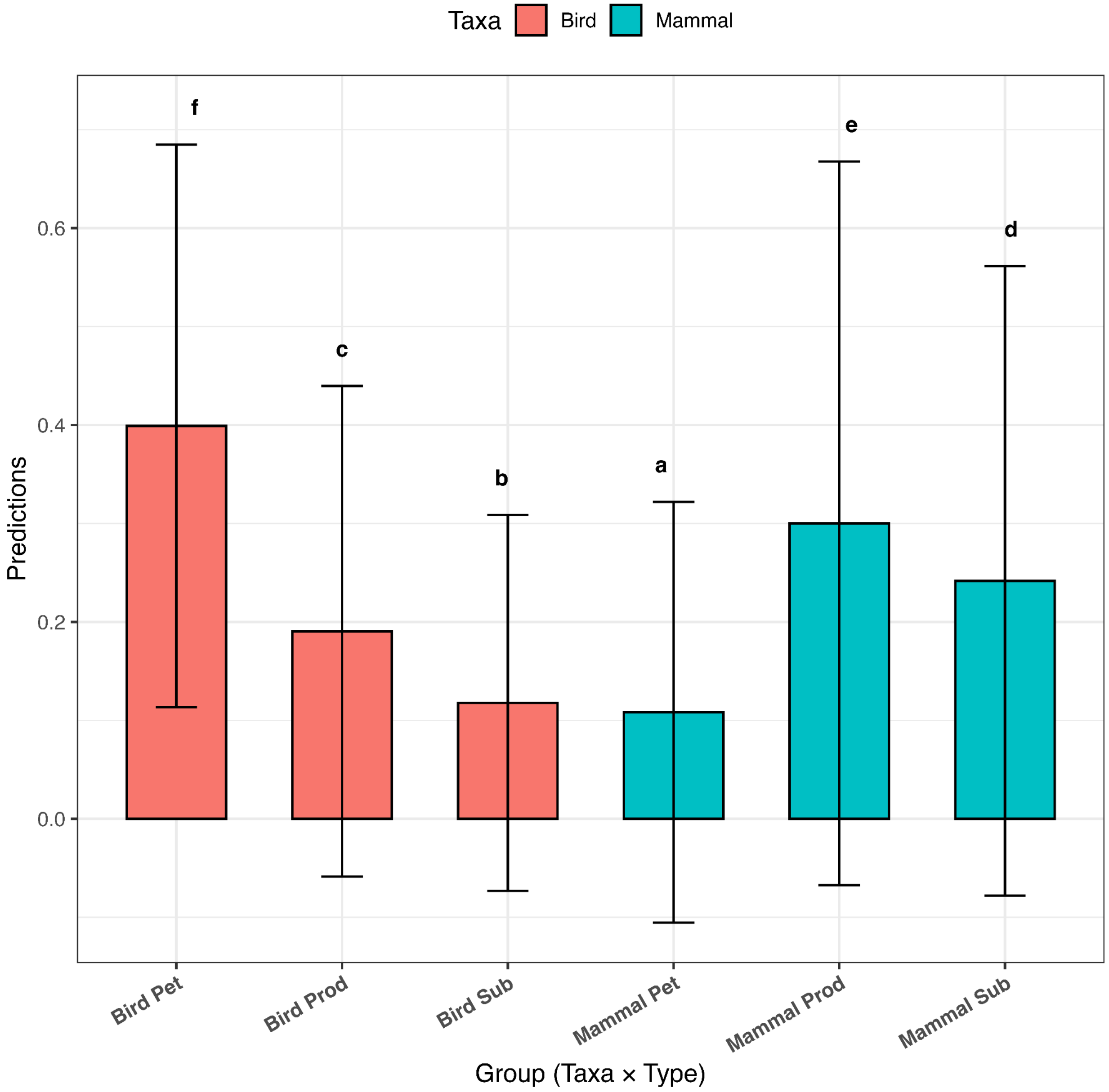


Figure S7. Predicted hunting likelihood of species based on traits and phylogeny.

Each bar shows the mean predicted probability of being hunted for a given purpose (pet, product, or subsistence), averaged across species. Birds are shown in red and mammals in blue. Error bars represent the standard deviation of predicted values across the species pool.

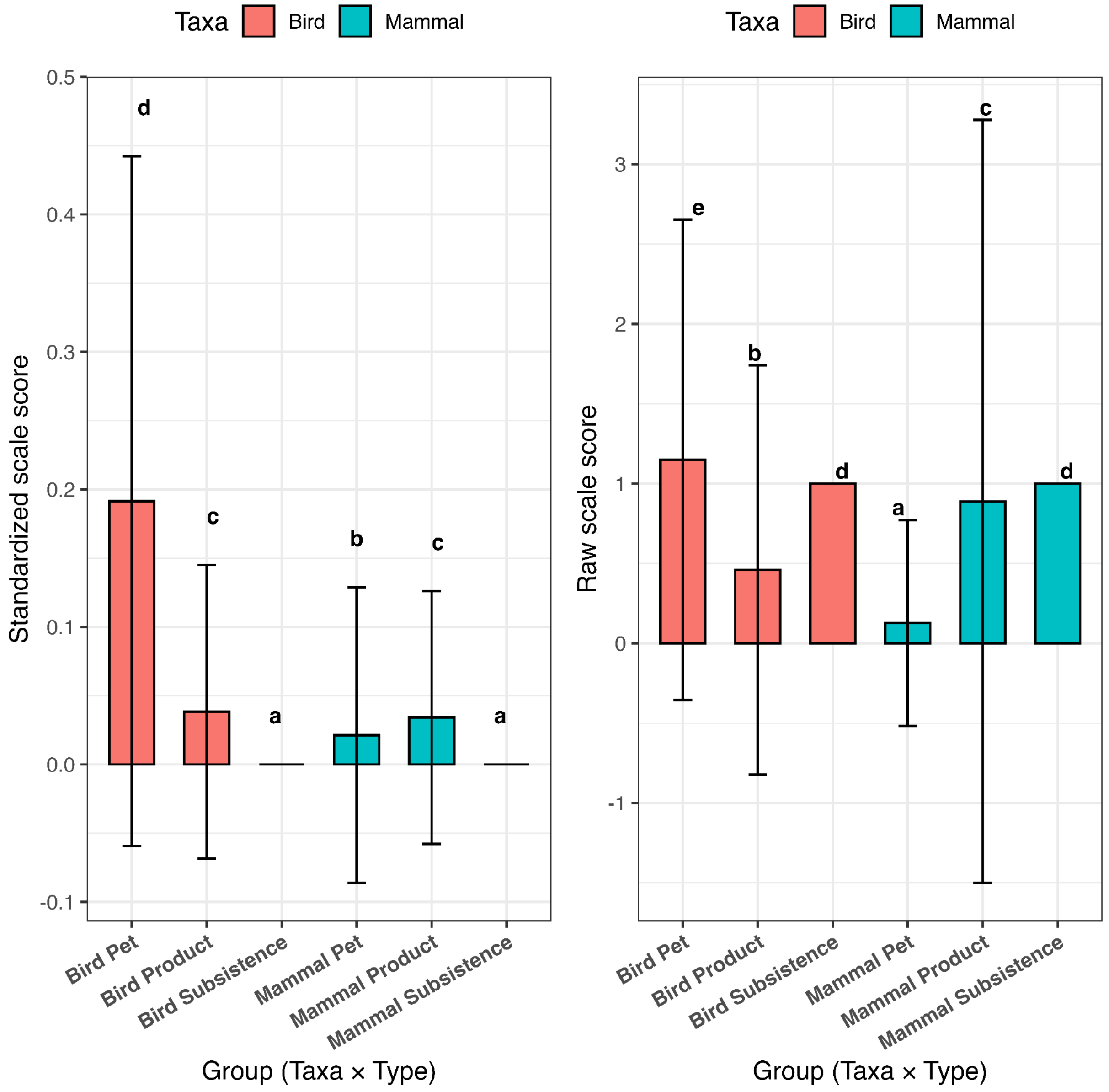


Figure S8. Distribution of trade scale scores across taxa and hunting purposes.

The left panel shows min–max scaled trade scores, with bars representing the mean and brackets indicating the standard deviation, across three hunting purposes: pet trade, product trade, and subsistence. Birds are shown in red and mammals in blue. The right panel displays the corresponding raw (unscaled) trade scores before standardization.

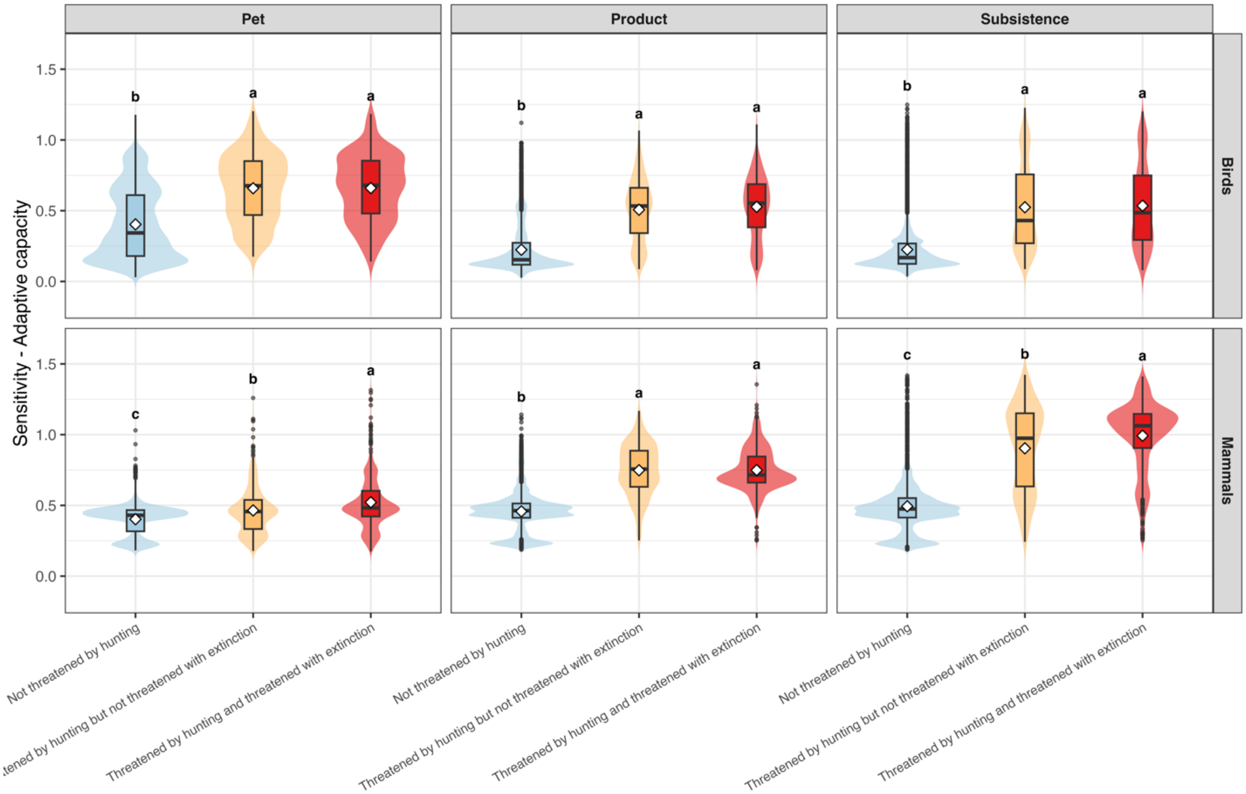


Figure S9. Summary of species-level Sensitivity - Adaptive capacity composite scores to hunting for tropical mammals and birds.

Violin plots show the distribution of scores across IUCN hunting threat categories, derived from the combination of IUCN threat status and hunting threat assessments. Species classified as threatened by hunting and at risk of extinction (i.e., listed as Vulnerable, Endangered, or Critically Endangered on the IUCN Red List) are shown in red. Species assessed as threatened by hunting but not considered globally threatened (i.e., listed as Least Concern or Near Threatened) are shown in yellow. Species not assessed as threatened by hunting are shown in blue. White diamonds represent the mean score for each category. Letters indicate significantly different groups based on post hoc pairwise comparisons of least-squares means with Šidák correction, where group “a” has the highest scores and group “c” the lowest. Post hoc tests were performed following the linear model: Sensitivity - Adaptive capacity ~ IUCN hunting threat category.

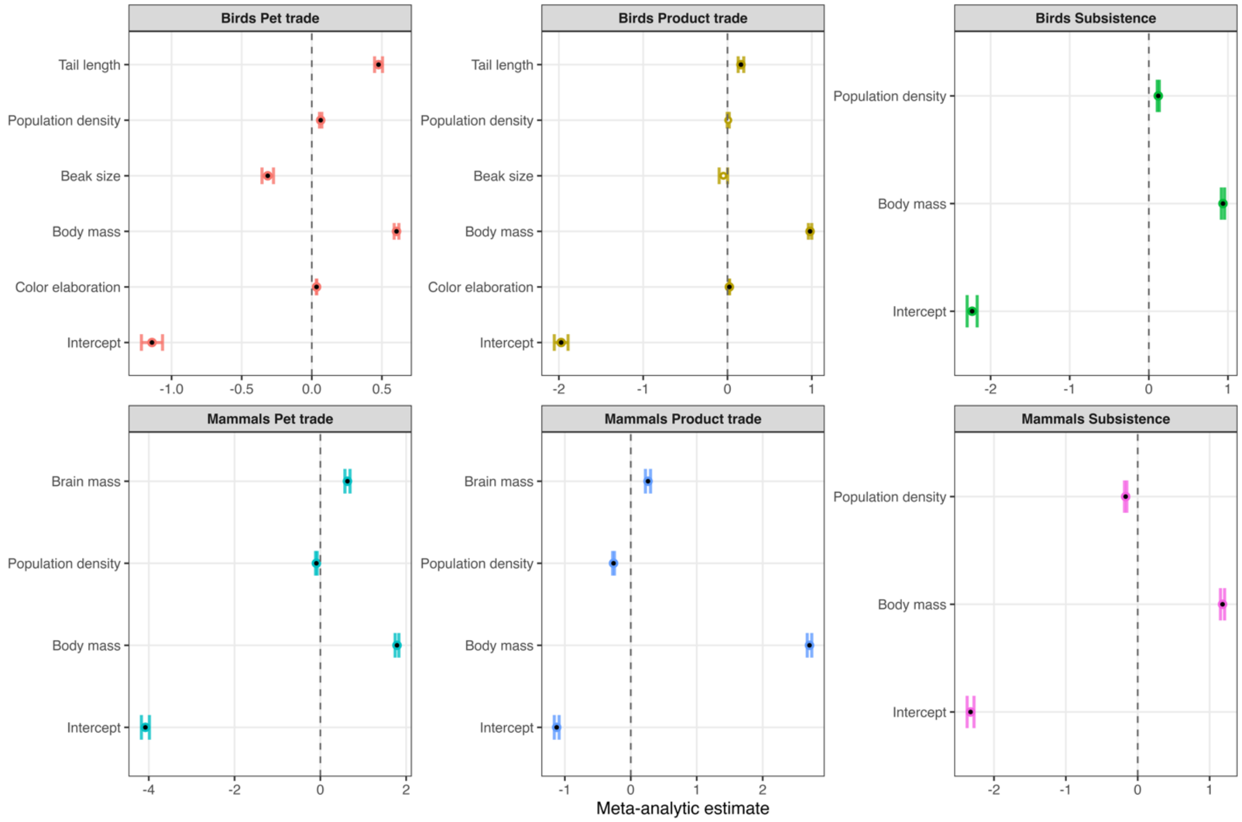


Figure S10. Trait importance in predicting species hunting status.

Importance of traits in predicting hunting status (1 = hunted, 0 = non-hunted) across 100 fitted generalized linear mixed-effects models. Tail length, population density, beak size and brain mass correspond to trait values controlled for body mass (i.e. residuals from body mass–trait regressions), and body mass was log-transformed and rescaled prior to analysis. Black dots indicate traits with effect sizes significantly different from zero across bootstrap iterations (95% confidence level), whereas white dots indicate non-significant effects.

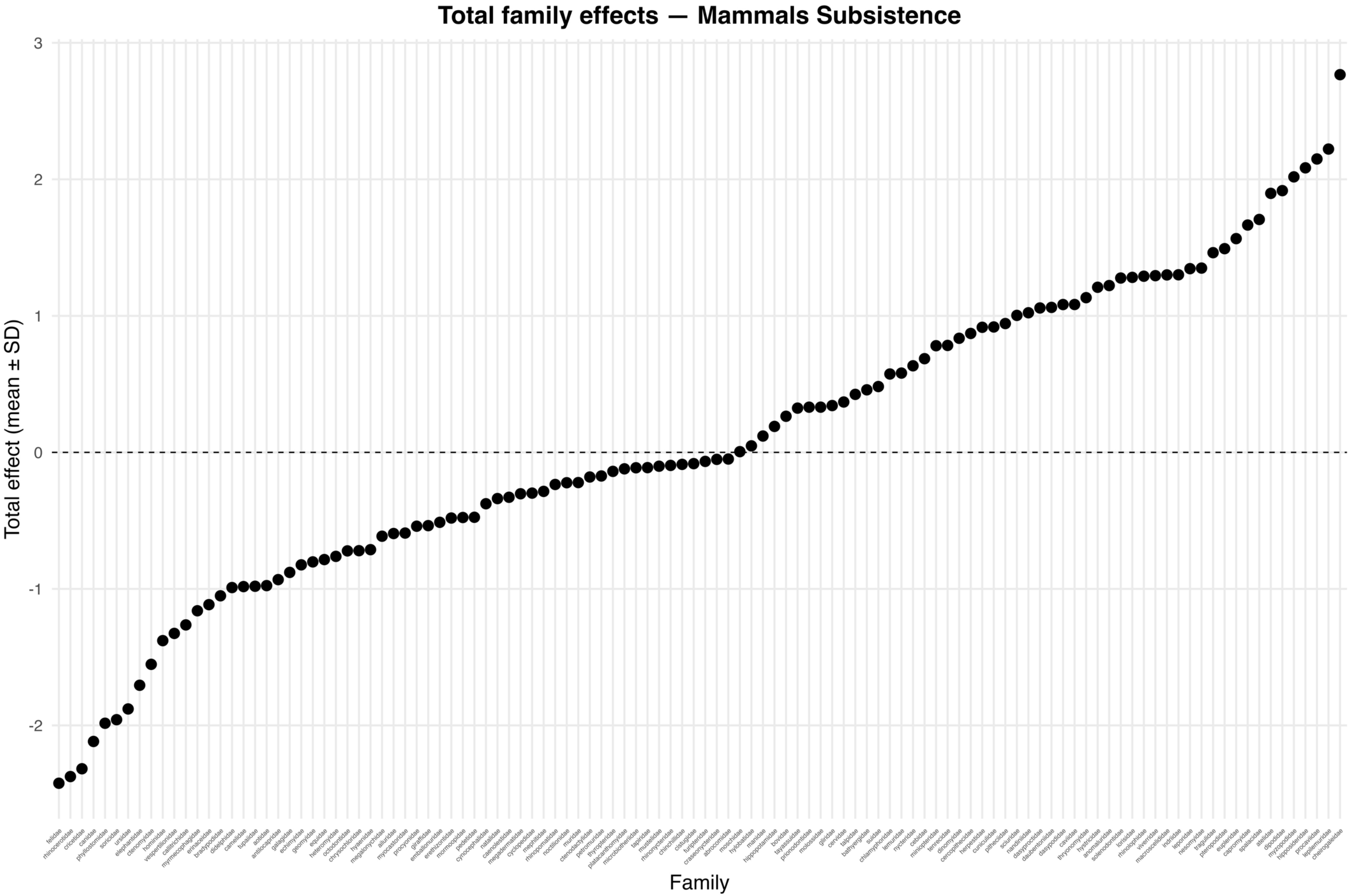


Figure S11. Family importance in predicting species hunting status for subsistence hunting of mammals.

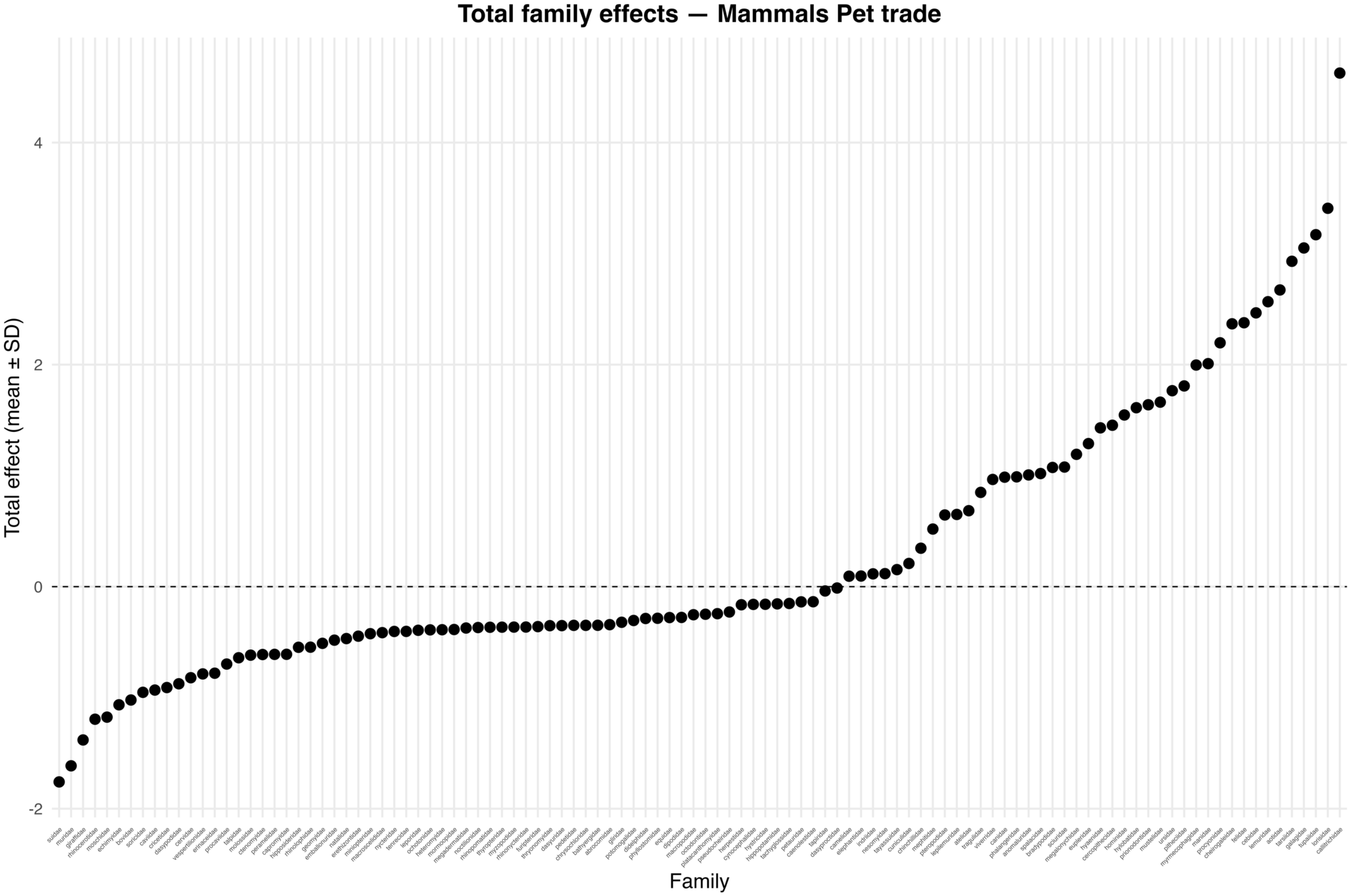


Figure S12. Family importance in predicting species hunting status for pet trade of mammals.

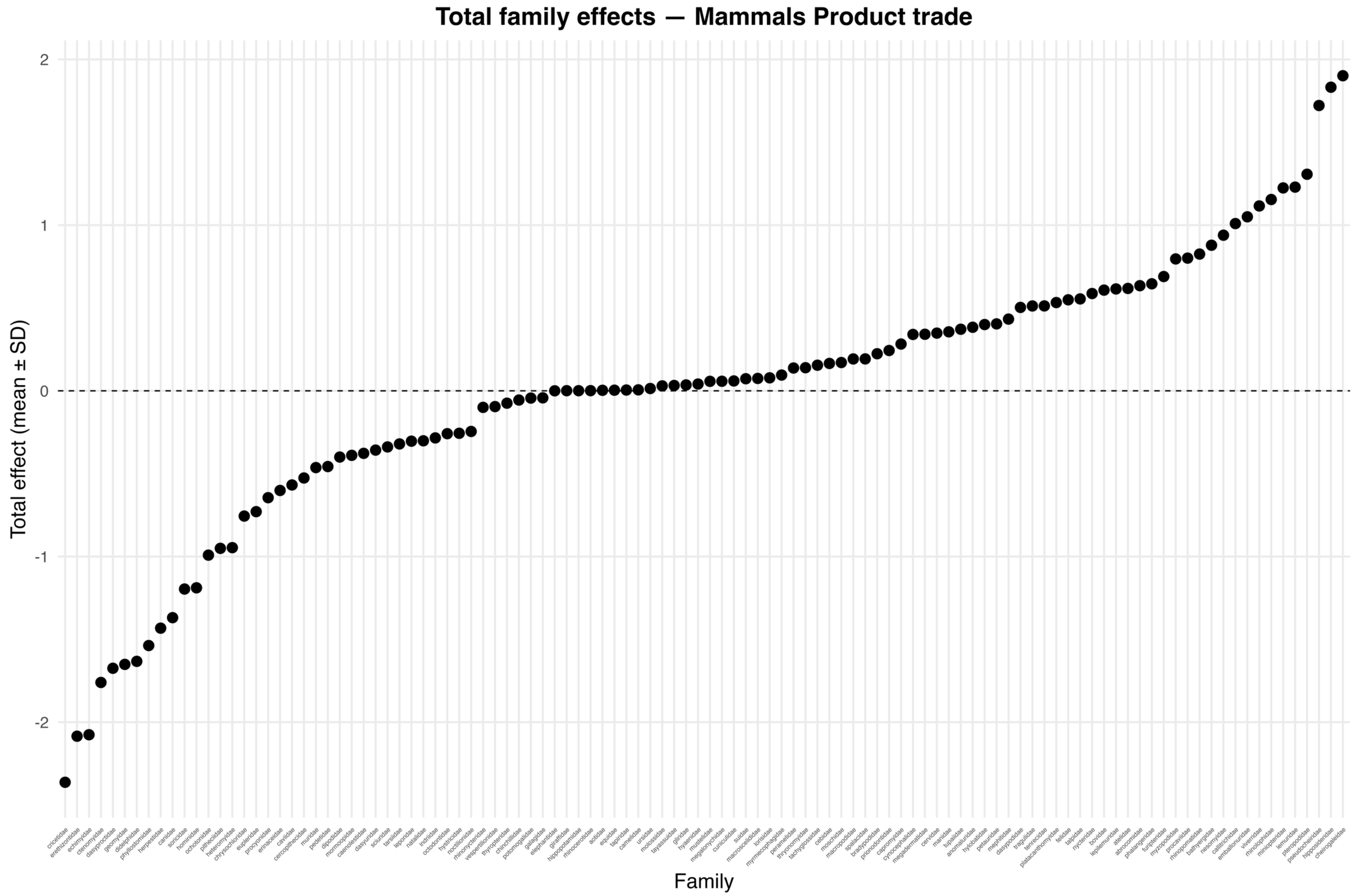


Figure S13. Family importance in predicting species hunting status for product trade of mammals.

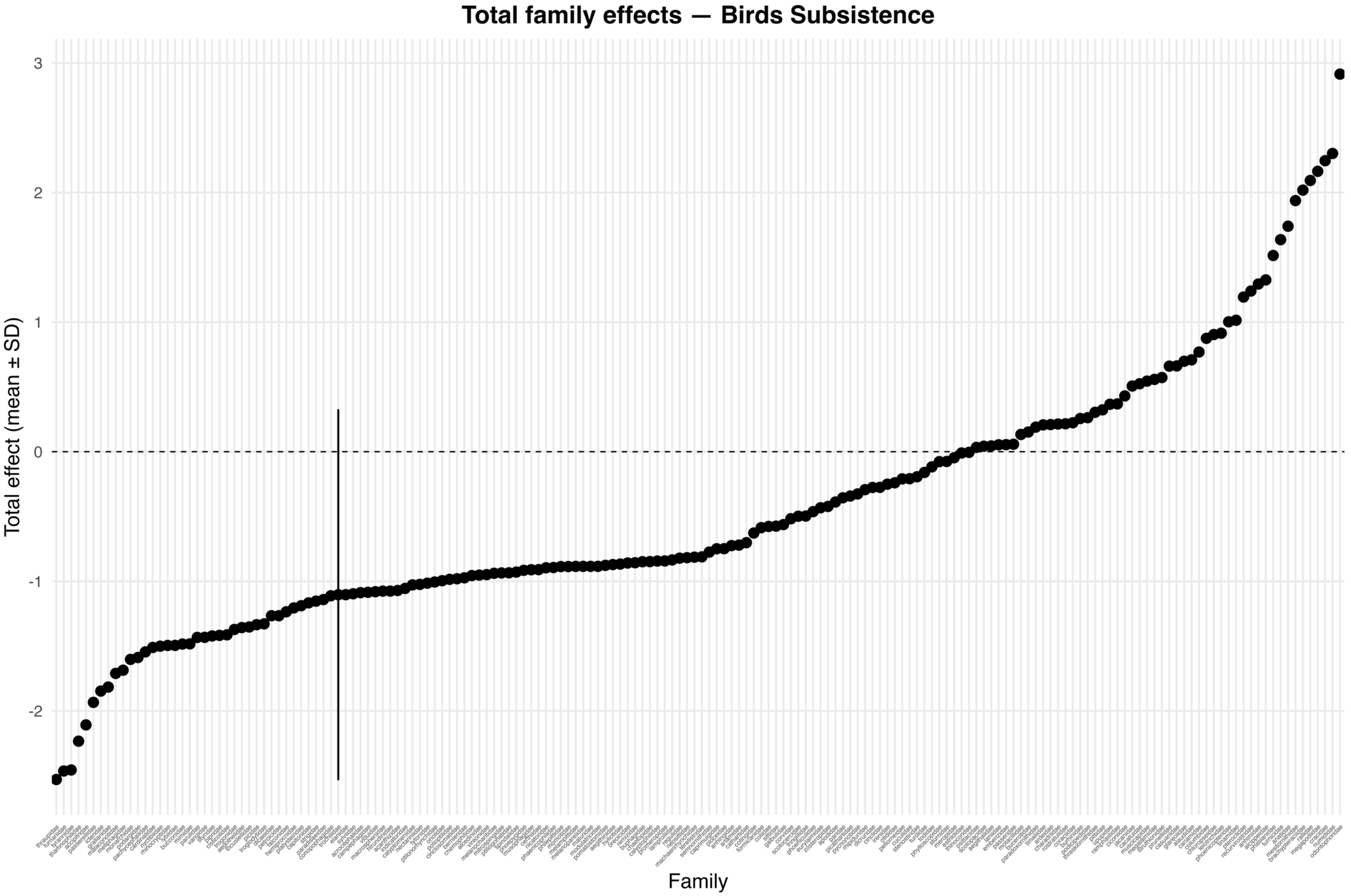


Figure S14. Family importance in predicting species hunting status for subsistence hunting of birds.

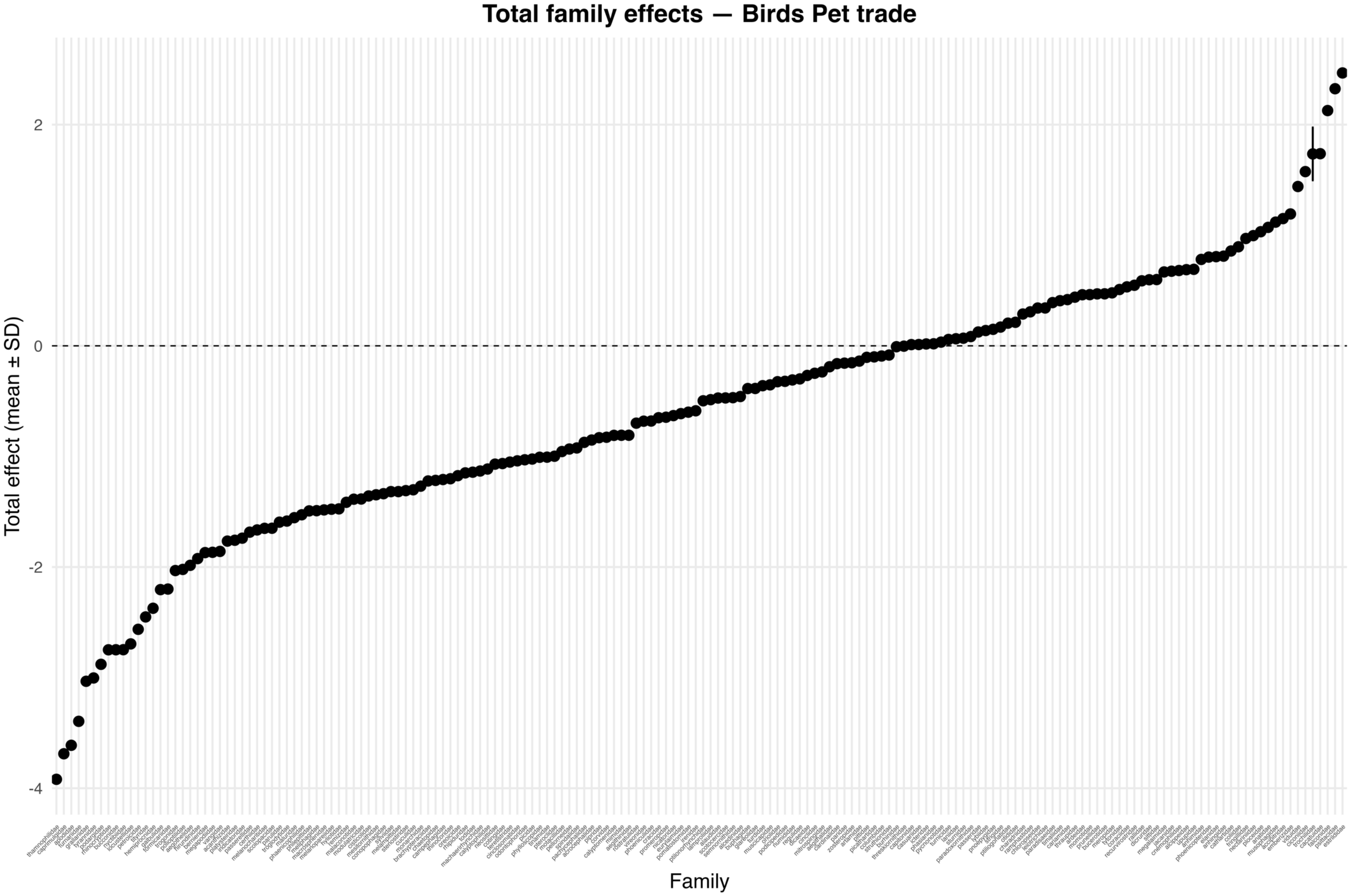


Figure S15. Family importance in predicting species hunting status for pet trade of birds.

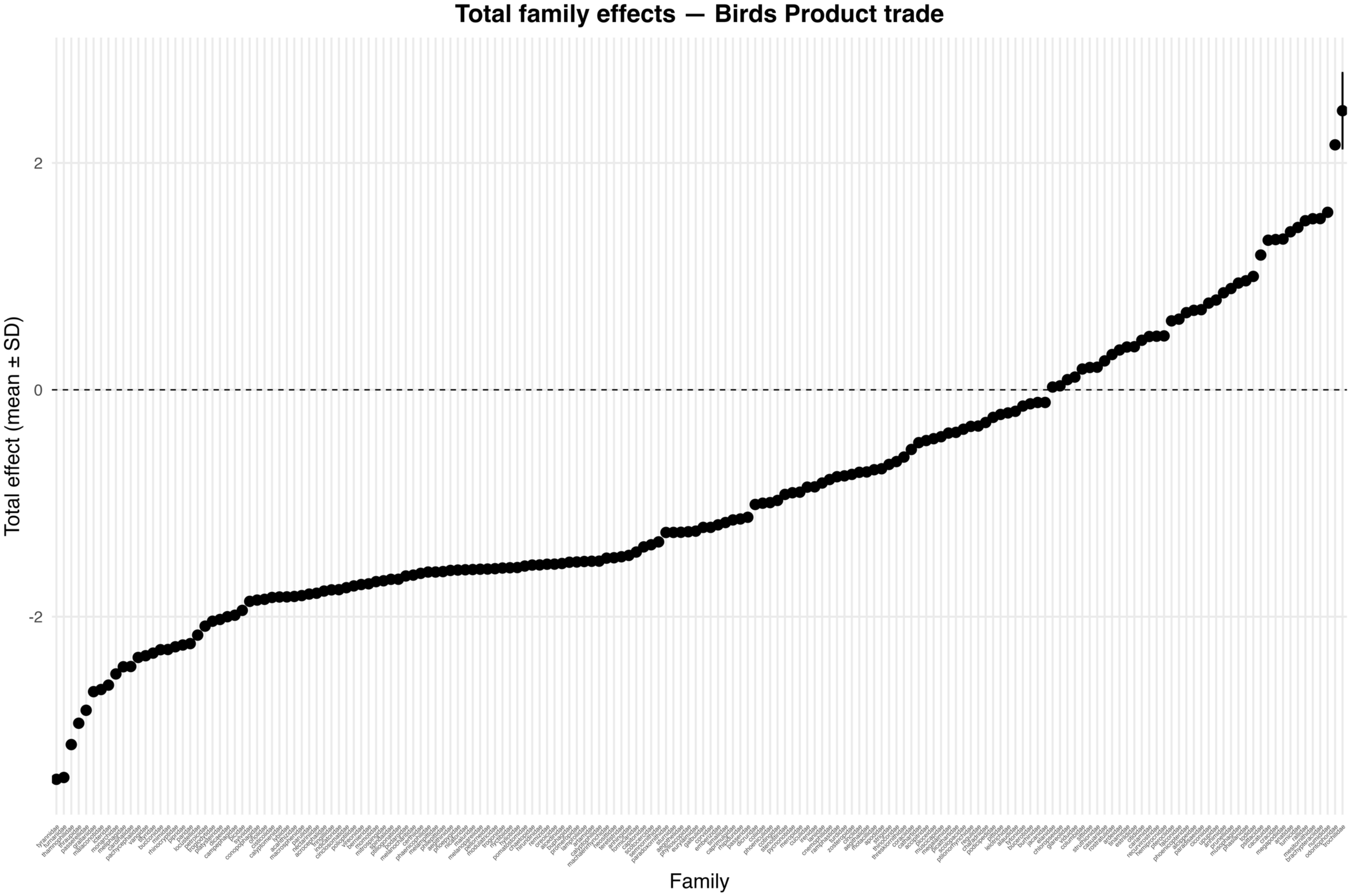


Figure S16. Family importance in predicting species hunting status for product trade of birds.

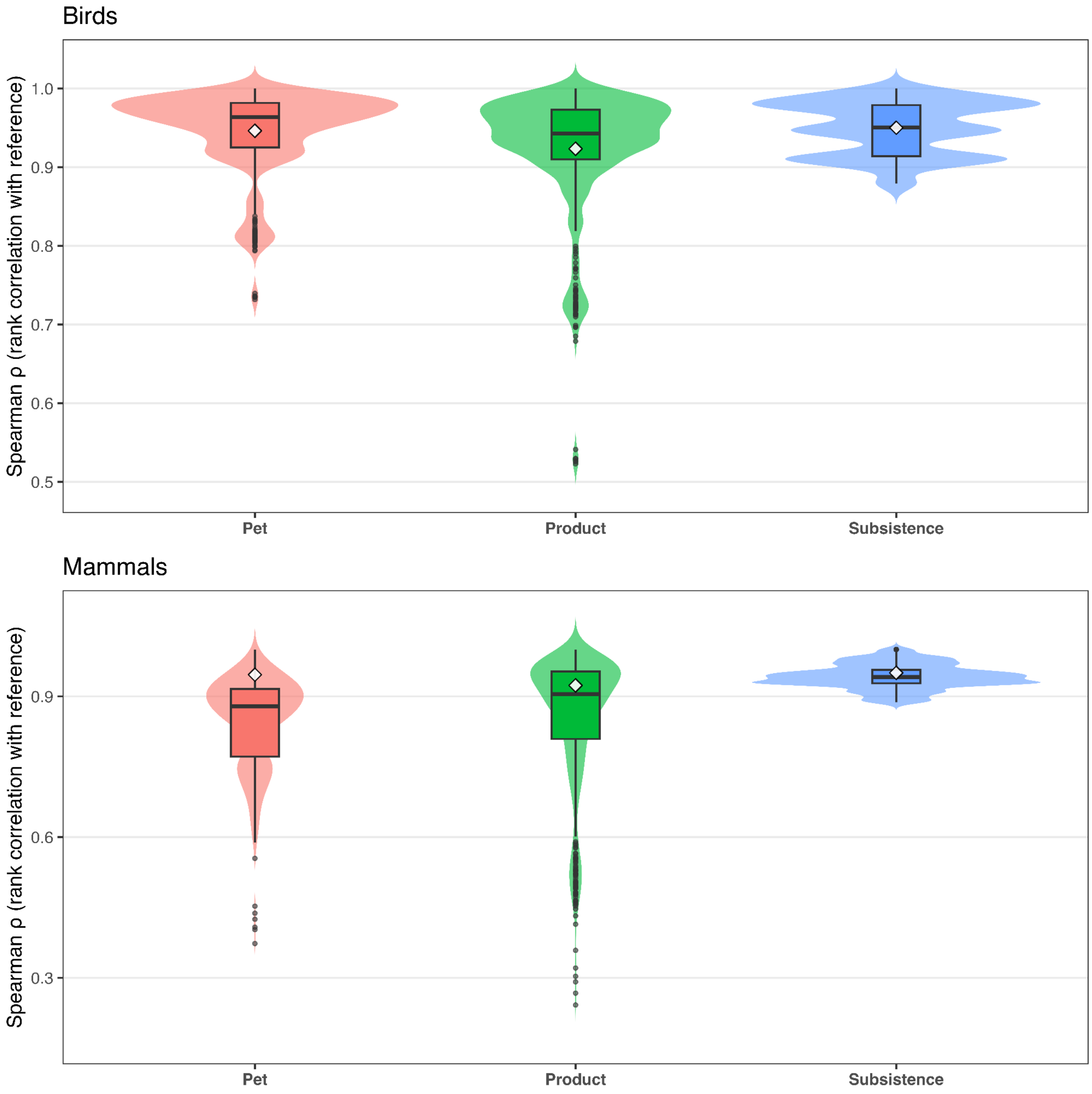
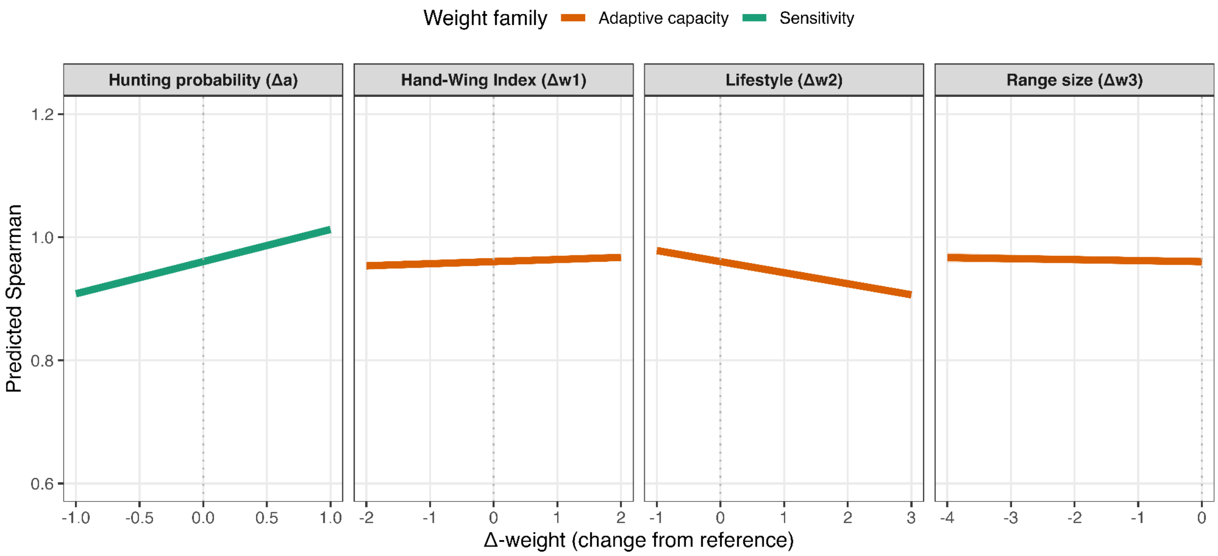


Figure S17. Effect of weighting scenarios on species' Sensitivity - Adaptive capacity scores.

Each point represents an alternative weighting scenario compared to the reference scenario used in the main analysis. The Spearman correlation coefficient indicates the rank correlation between species scores under the alternative and reference scenarios. Lower correlation values reflect greater sensitivity of species rankings to changes in weighting, highlighting the influence of score composition on vulnerability estimates. The top panel represent birds and bottom mammals.

Birds



Mammals

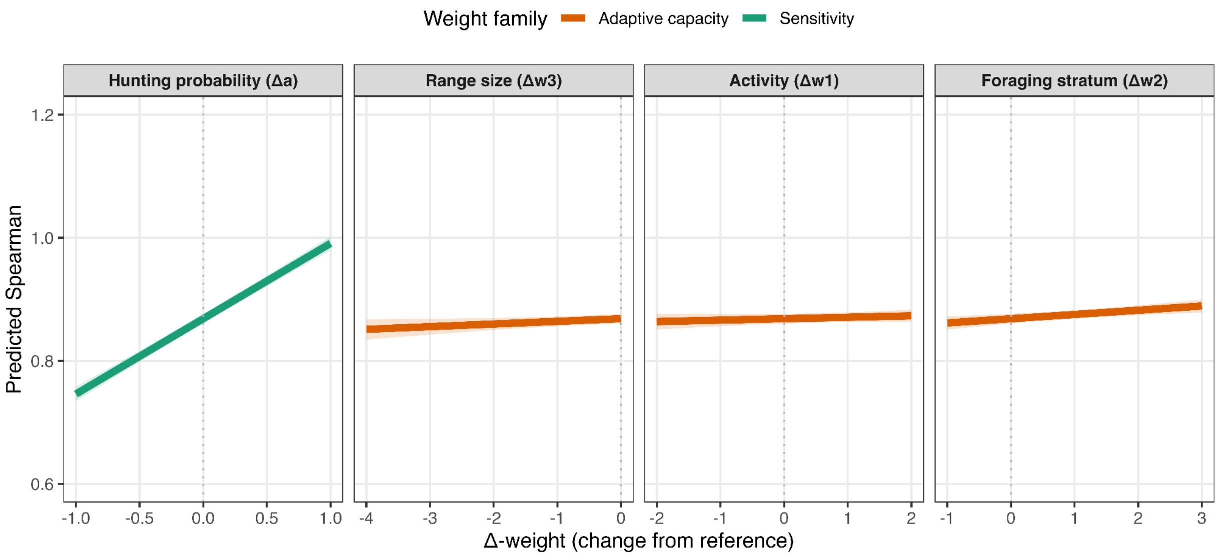


Figure S18. Influence of component weight changes on Sensitivity - Adaptive capacity score deviations.

Each line represents the marginal effect of changing the weight of a single component (trait) within the Sensitivity or Adaptive capacity score on the Spearman correlation between the alternative and reference scoring scenarios. Correlation reflects how much species-level rankings shift when the weight of a component is changed. Green lines correspond to components from the Sensitivity score; orange lines to those from Adaptive capacity. Because weights within each score family were constrained to sum to a constant total, the influence of any one component is dependent on the weights of the others, thus one component per score family is omitted for interpretability.