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Global impacts of anthropogenic threats on bird and mammal diet functional groups

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ABSTRACT

Anthropogenic threats vary in how they affect individual species, functional diversity, and consequently, ecosystems as a whole. However, which groups of species are most affected by specific threats remains poorly understood. To evaluate which bird and mammal functional groups are most affected by specific threats, we use data aggregated by the International Union for Conservation of Nature (IUCN) to calculate the extent to which diet functional groups and body size explain the global impacts of the most common anthropogenic threats. For both birds and mammals, we found that terrestrial vertivores, aquatic predators, and frugivores (including mammalian nectivores and granivores) are most negatively impacted by anthropogenic threats, with crops and livestock as the top threats to vertivores, climate change and pollution for aquatic predators, and logging for the frugivores. Threats associated with plantations and recreation/work affect less than 5% of species across functional groups. Body mass is positively correlated with the impact of anthropogenic threats especially for hunting, such that larger species are substantially more threatened by hunting than smaller species. Our results reveal that bird and mammal vulnerabilities vary by diet functional group, body mass, and the type of anthropogenic threat. Given our findings that functionally important groups (i.e., predators and frugivores) are disproportionately impacted by multiple anthropogenic threats, and that individual threats differ in their severity across functional groups, we recommend targeting conservation actions to mitigate threats in a manner that will preserve critical ecosystem functions.

1. Introduction

Biodiversity is declining globally due to anthropogenic activities (Bellard et al., 2022; Harfoot et al., 2021), such that ~18% of vertebrate species are now threatened with extinction (IUCN, 2024a). The degree and severity of anthropogenic threats on biodiversity is commonly measured by assessing impacts on species richness, the total number of species within a given area (Ceballos and Brown, 1995; Gotelli and Colwell, 2001; Maxwell et al., 2016; Tilman et al., 2017). However, this approach does not account for the variable roles that species play within ecosystems. Biodiversity loss not only reduces taxonomic diversity, but can also lead to decreased functional diversity, i.e. the range of traits, activities, and services contributed by organisms (Ali et al., 2023; Brodie et al., 2021; Sayol et al., 2021). The ongoing loss of threatened species is predicted to reduce functional diversity across many taxa including mammals,

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birds, amphibians, reptiles, and fish (Ali et al., 2023; Brodie et al., 2021; Carmona et al., 2021; Cooke et al., 2019; Toussaint et al., 2021). In many cases, threatened species are functionally unique, so losing these species can greatly reduce functional diversity (e.g., Carmona et al., 2021; Cooke et al., 2019; Toussaint et al., 2021).

To mitigate the impacts of global changes on functional diversity and set conservation priorities, it is critical to understand which functional groups are most affected by anthropogenic threats. Generally, species with the highest extinction risks tend to be large in size (Atwood et al., 2020; Cardillo et al., 2005; Gaston and Blackburn, 1995). Large-bodied species often have slow life histories (e.g., long generation times, high age to maturity) and low population densities that make recovery from the impacts of threatening processes difficult (Gaston and Blackburn, 1995; Purvis et al., 2000). Poor dispersal ability, small range sizes, and habitat specificity are also correlated with extinction risk (Chichorro et al., 2022; O'Grady et al., 2004; Purvis et al., 2000). Furthermore, extinction risk can be heavily influenced by the diet and trophic level of a species. Species that have specialized diets or belong to higher trophic levels (e.g., predators) are more vulnerable to extinction than generalist or omnivorous species and those occurring at lower trophic levels (Dobson et al., 2006; Estes et al., 2011; Machado et al., 2023; Purvis et al., 2000). Because anthropogenic threats disproportionately impact species with distinct functional traits, ecosystems risk losing the unique functions that these species provide. For example, small-bodied mammals (e.g., bats, rodents) contribute to pollination, seed dispersal, and pest control, while large-bodied mammals (e.g., elephants, whales, lions) tend to impact ecosystem structure and function through bottom-up and top-down processes such as nutrient cycling and predation (Lacher et al., 2019). Among birds, nectarivores, frugivores, and scavengers are disproportionally predicted to go extinct, with important consequences on ecological functions related to pollination, seed dispersal, and decomposition respectively (Şekercioğlu et al., 2004).

While anthropogenic threats generally affect certain types of species, different threats also vary in the types of species they impact (Brodie et al., 2015; Poulsen et al., 2011). Exploitation threats (e.g., hunting, fishing) tend to affect large-bodied species with slow life history traits because these species are unable to offset direct mortality caused by over-exploitation (Osuri et al., 2020; Owens and Bennett, 2000; Ripple et al., 2017). In contrast, habitat loss and degradation disproportionately affect small-bodied species with restricted geographic ranges (Owens and Bennett, 2000; Ripple et al., 2017), though carnivores may also be affected by land use change (Newbold et al., 2020). For example, in tropical forests, hunting disproportionately impacts large-bodied mammal and bird species, and certain functional groups (i.e., carnivores, frugivores, herbivores, granivores), while forest conversion affects mammal and bird species across functional groups (i.e., carnivores, frugivores, herbivores, granivores, insectivores, nectivores, generalists) and body sizes (Osuri et al., 2020).

To mitigate the effects of biodiversity loss on ecosystem function, we need to understand the types of species at risk. Many studies have used traits to assess general extinction risk regardless of the type of anthropogenic threat (e.g., Chichorro et al., 2022; O'Grady et al., 2004; Purvis et al., 2000), while other studies have assessed whether threats affect functional diversity as a whole (Brodie et al., 2021; Matuoka et al., 2020). However, anthropogenetic threats vary in the types of species they affect, and we know very little about which types of species are most affected by which types of threats.

In this study, we evaluate the extent to which the most prevalent anthropogenic threats impact bird and mammal functional groups, defined by diet and body mass. Diet and body mass are two functional traits that characterize the role of species within communities and are explicitly linked to ecosystem functions (Wilman et al., 2014). We focus on birds and mammals because these taxa are particularly well studied with comprehensive functional trait data that are publicly available (Faurby et al., 2020; Tobias et al., 2022). All described bird species and 89% of described mammal species have been evaluated by the International Union for Conservation of Nature (IUCN) and assigned anthropogenic threat scores (IUCN, 2024a), which we use to identify the specific threats that target individual species. Our research questions are: i) which anthropogenic threats have the greatest impacts on birds and mammals worldwide, ii) which diet groups are most affected by each of the most common anthropogenic threats, and iii) what is the role of body mass on the impact of multiple anthropogenic threats? By evaluating species groups according to their diets and body sizes, our study elucidates how various ongoing anthropogenic stressors may impact ecological functions, providing critical information on the complex roles that human activities have on global ecosystems.

2. Methods

2.1. Species threats

The IUCN Red List of threatened species is the most comprehensive database on the conservation status of species worldwide. The database summarizes extinction risk of species by specific categories (extinct, extinct in the wild, critically endangered, endangered, vulnerable, near threatened, least concern, data deficient) and includes the threats observed or hypothesized to be causing declines of species (IUCN, 2024a). Threats are categorized following a standard hierarchical classification method (IUCN, 2024b; Salafsky et al., 2008). At the highest level are Level 1 threats, which are large, umbrella categories that include: "agriculture & aquaculture", "biological resource use", "pollution", "climate change & severe weather", "energy production & mining", "geological events", "human intrusions & disturbance", "invasive species & diseases", "natural system modifications", "transportation & service corridors", "residential & commercial development", and "other options". Within the "agriculture & aquaculture" category, for example, are Level 2 threat categories including "annual and perennial non timber crops", "wood and pulp plantations", "livestock and ranching", and "marine and freshwater aquaculture" (IUCN, 2024a). Threats data contain quantitative information on the timing (when the threat occurred), scope (extent to which populations are being impacted), and severity (rate at which a threat precipitates declines of populations) of each threat on the evaluated species (IUCN, 2024a). Following the IUCN Threat Impact Scoring System Version 1.0 (IUCN, 2024b), the overall impact of each threat on the persistence of a species is estimated by summing timing, scope, and severity

scores to categorize a threat as high impact, medium impact, low impact, or no impact (IUCN, 2024a). The data from the IUCN includes the overall impact of each threat and threat impact scores. All species included in our analyses had threat scores for timing, scope, and severity.

We categorized threats to each species following the IUCN Threats Classification Scheme Version 3.3 (IUCN, 2024b), using Level 1 categories with a few exceptions. For the Level 1 categories of "agriculture & aquaculture" and "biological resource use", we used Level 2 threat categories because the Level 1 categories contain diverse threats that we felt were worth considering separately. For example, crops and livestock (both considered "agriculture & aquaculture") impact different regions and ecosystems (Chaudhary et al., 2016), and logging and hunting (both considered "biological resource use") affect different species (Brodie et al., 2015; Poulsen et al., 2011). We also combined the Level 1 threat categories of "residential & commercial development", "energy production and mining", and "transportation & service corridors" into a new category we call "infrastructure development" because these threats individually affected relatively few species and because we assume that different types of infrastructure development impact species in broadly similar ways (Simkins et al., 2023; Sloan and Izquierdo, 2026). After completing this process, we obtained a total of 16 threat categories and retained the 10 most common anthropogenic threats across birds and mammals (Appendix A: Table A.1): (1) annual and perennial non-timber crops (crops), (2) wood and pulp plantations (plantations), (3) livestock farming and ranching (livestock), (4) hunting and collecting terrestrial animals (hunting), (5) logging and wood harvesting (logging), (6) human intrusions and disturbance (recreation/work), (7) invasive and other problematic species, genes, and diseases (invasives/diseases), (8) pollution, (9) climate change and severe weather (climate change), and (10) infrastructure development. Of the threat categories used, five (crops, logging, livestock, plantations, and infrastructure development) are broadly associated with habitat loss/modification, which is often ranked as the top risk to biodiversity (Bellard et al., 2022).

We downloaded lists of extant mammals (5980 species) and birds (11,197 species) together with the anthropogenic threats affecting each species from the IUCN Red List database in March 2024 (Version 2024–1) using the *rredlist* package (Gearty and Chamberlain, 2024; IUCN, 2024a). For all mammal and bird species, we determined the threat impact level (i.e., high, medium, low, or no impact) for each of the ten threat categories. For later analyses, we considered species as either not affected (no or low impacts) or affected (medium or high impacts) by a given threat.

We also downloaded IUCN status data using the *rredlist* package for all extant mammal and bird species; species with an IUCN status of "extinct" or "extinct in the wild" were excluded from all analyses. We also excluded species that had an IUCN status of "Data Deficient" (40 bird species and 827 mammal species), as we believe that the anthropogenic threat data for these species are incomplete and thus unreliable. For the remaining species (birds and mammals), we considered threats where the timing was categorized as "ongoing". We considered all species with a threat status of critically endangered, endangered, or vulnerable as "threatened" and species categorized as near threatened or least concern as "non-threatened."

2.2. Functional groups and body mass

We obtained diet functional group and body mass data for birds from the AVONET database (Tobias et al., 2022). We used AVONET trophic niche categories as diet functional groups, though we added scavenger (the least common category) to vertivore because there were so few scavengers (22 species), and combined herbivore aquatic (the second-least common category, 83 species) and herbivore terrestrial (the third-least common category, 95 species), which left us with eight diet functional groups for birds: aquatic predator, frugivore, granivore, herbivore, invertivore, nectarivore, omnivore, and vertivore. We taxonomically aligned functional group and body mass data from AVONET with the anthropogenic threat data we derived from the IUCN database (Version 2024–1). We used the IUCN bird species list and synonyms downloaded in March 2024 through the *rredlist* package (Gearty and Chamberlain, 2024; IUCN, 2024a). Species that lacked body mass and trophic niche data (56 species, 0.5% of total species) were assigned genus-level data (i.e., genus-average body mass, the most common functional group for species in the genus). Three species that were missing trait data and had no congeners were excluded. To evaluate the impact of using genus-level data, we made predictions for a subset of species with known traits and determined that our approach was able to correctly identify diet functional groups for 80% of species. Additionally, predictions of species-level body mass using genus-level traits were within 21% of true body mass on average (mean absolute difference = 21%, SD = 31%). This data processing left us with a database of anthropogenic threats, functional groups, and body mass data for 10,990 bird species (Appendix A: Fig. A.1).

We obtained mammal body mass data from the PHYLACINE database (Version 1.2.1) and derived diet functional groups using data from the PHYLACINE and EltonTraits databases (Faurby et al., 2018, 2020; Kissling et al., 2014; Wilman et al., 2014). Using the PHYLACINE database, we combined species habitat attributes (i.e., marine, freshwater, terrestrial, aerial) and coarse diet categories (i.e., invertebrates, vertebrates, plants) to derive mammal functional groups that aligned with our bird functional groups described in the AVONET database. The five mammal functional groups included: aquatic predator (marine or fresh water with plant diet less than 50%), invertivore (terrestrial or aerial with an invertebrate diet greater than 50%), vertivore (terrestrial or aerial with vertebrate diet greater than 50%; including scavengers), herbivore (plant diet greater than 50%) and omnivore (invertebrate, vertebrate, and plant diets less than 50% each). We used the 50% threshold, following a similar approach of defining bird dietary functional groups within the AVONET database (Tobias et al., 2022). For birds, our herbivore category includes both aquatic and terrestrial herbivores because there are many comparable species in both groups (e.g., both aquatic and terrestrial ducks and geese) and all aquatic avian herbivores are only semi-aquatic, facing similar threats to their terrestrial counterparts. However, for mammals, there are only four aquatic herbivores (manatees and dugong) that live entirely in marine environments, and these species are exposed to very different threats than terrestrial mammal herbivores. We thus omitted the four sirenian species from our mammal herbivore group. Using the EltonTraits database, we further divided the herbivore functional group into two groups: the first group described frugivore, nectivore, and

granivore species, and the second group contained species that feed on other plant parts (e.g., leaves). A species was assigned the frugivore/nectivore/granivore functional group when the combined proportion of fruit, nectar, and seed diet categories was greater than the "other plant parts" category – otherwise the herbivore functional group was assigned. We ended with a total of six diet categories for mammals: aquatic predator, vertivore, invertivore, omnivore, herbivore, and frugivore/nectivore/granivore. We aligned our functional group and body mass data with the anthropogenic threat data derived from the IUCN (Version 2024–1) using the *rredlist* package (Gearty and Chamberlain, 2024) to harmonize taxonomic synonyms. For species that had no trait data (313 species, 6% of total species), we used genus-level data to assign the functional group (i.e., the most common functional group of the genus) and body mass (genus-level average). A total of 15 mammal species lacked trait information at the genus level and were excluded from the database. As with birds, we tested the accuracy of assigning genus-level data for a subset of mammal species with known trait data and found that the correct diet functional group was assigned for 97% of species, with predictions of species-level body mass falling within 36% of true body mass on average (mean absolute difference = 36%, SD = 51%). This data processing left us with a database of anthropogenic threats, functional groups, and body mass for 5048 mammal species (Appendix A: Fig. A.1).

2.3. Logistic regression model

We examined the relationship between bird and mammal functional groups and anthropogenic threats using logistic regression. For each anthropogenic threat, we created a binary response variable for every species by assigning threat impact scores to either not affected (no & low impacts) or affected (medium & high impacts). We estimated the probability of a species being impacted by a threat as a function of diet functional group, running separate models for each of the ten threats and for both birds and mammals, resulting in twenty models. These models had different response variables (e.g., probability of being impacted by hunting for mammals) but the same explanatory variables (functional groups). Each functional group had a separate intercept representing the proportion of species in that functional group affected by the particular threat. As a sensitivity analysis, we also reran these models excluding the 56 bird and 313 mammal species with genus-level imputed trait data.

We then ran another analysis to evaluate the relationship between functional groups and anthropogenic threats while accounting for the effect of body mass. For this model, we estimated the probability of a species being impacted by a given threat as a function of both diet functional group and body mass. As with the first models, we ran separate models for each threat for both birds and mammals.

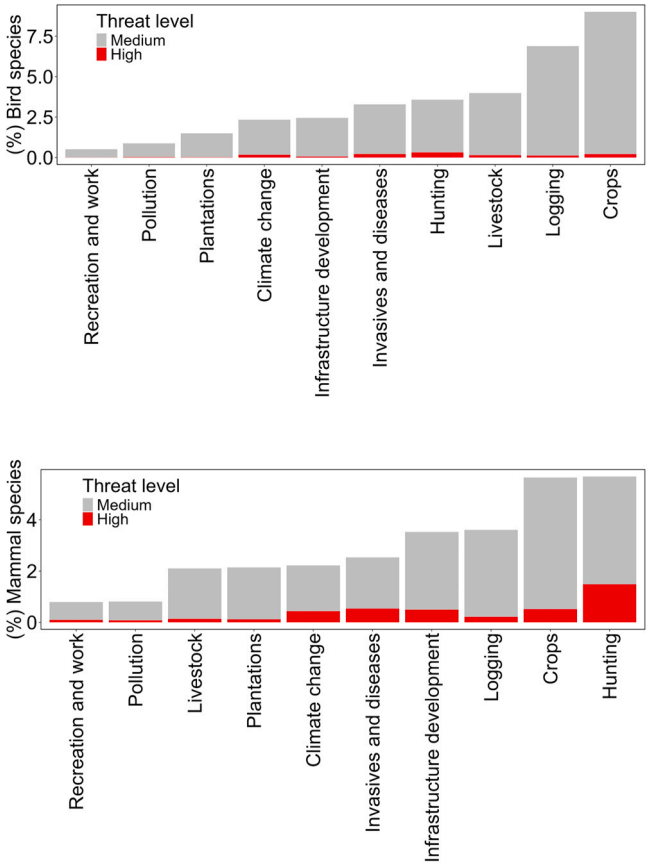

Fig. 1. Percent of birds (top) and mammals (bottom) negatively impacted by each anthropogenic threat with medium and high impact scores. Threats are arranged on the x-axis from least to most species impacted.

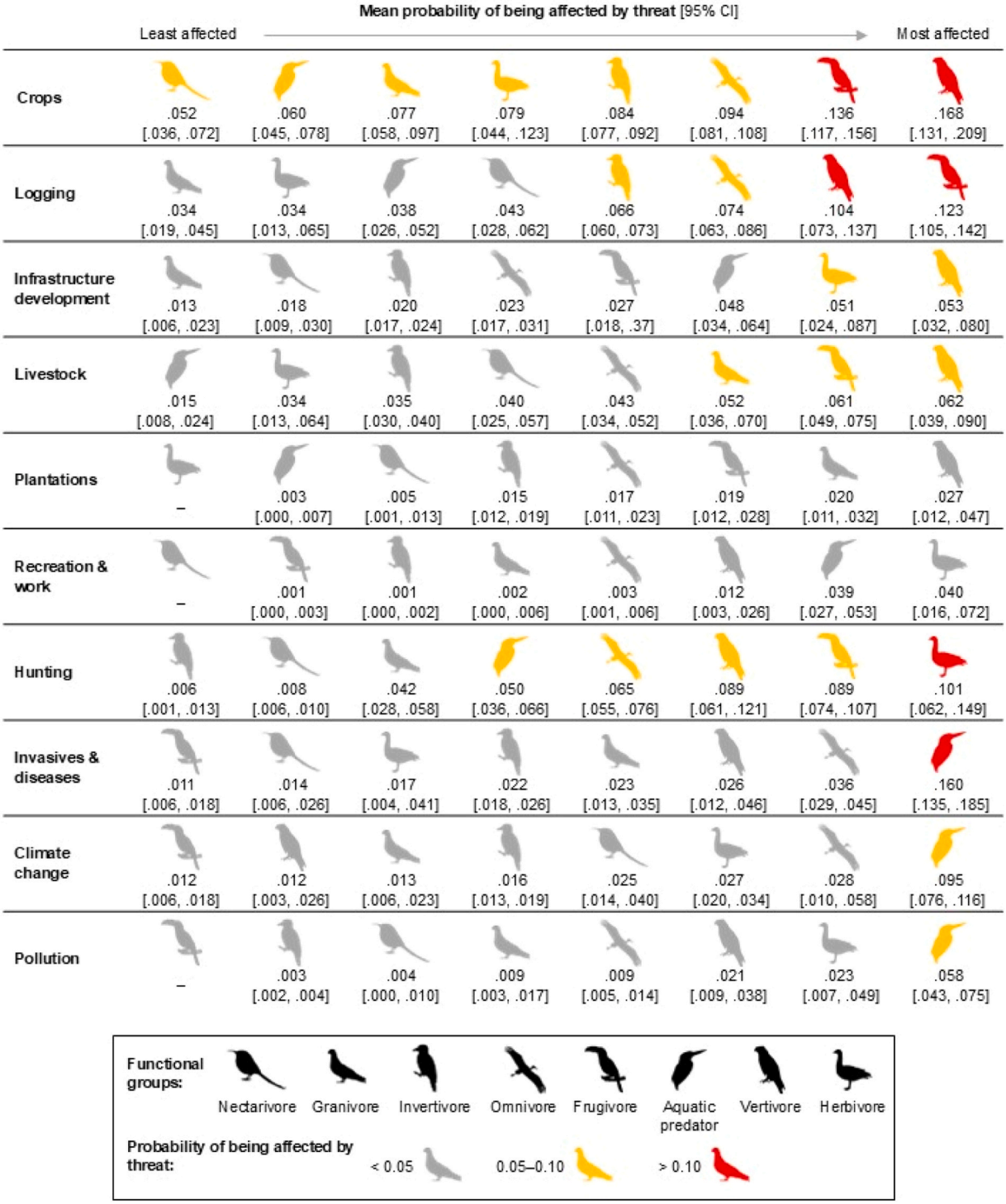

Fig. 2. Probability that a bird species in each functional group is negatively impacted by each anthropogenic threat. Mean probability is shown with 95% credible intervals in brackets. Functional groups in the legend (black silhouettes) are arranged left to right from smallest to largest mean body mass. A dash indicates that no species in the functional group was affected by the threat. Silhouettes were obtained from Phylopic (www.phylopic.org).

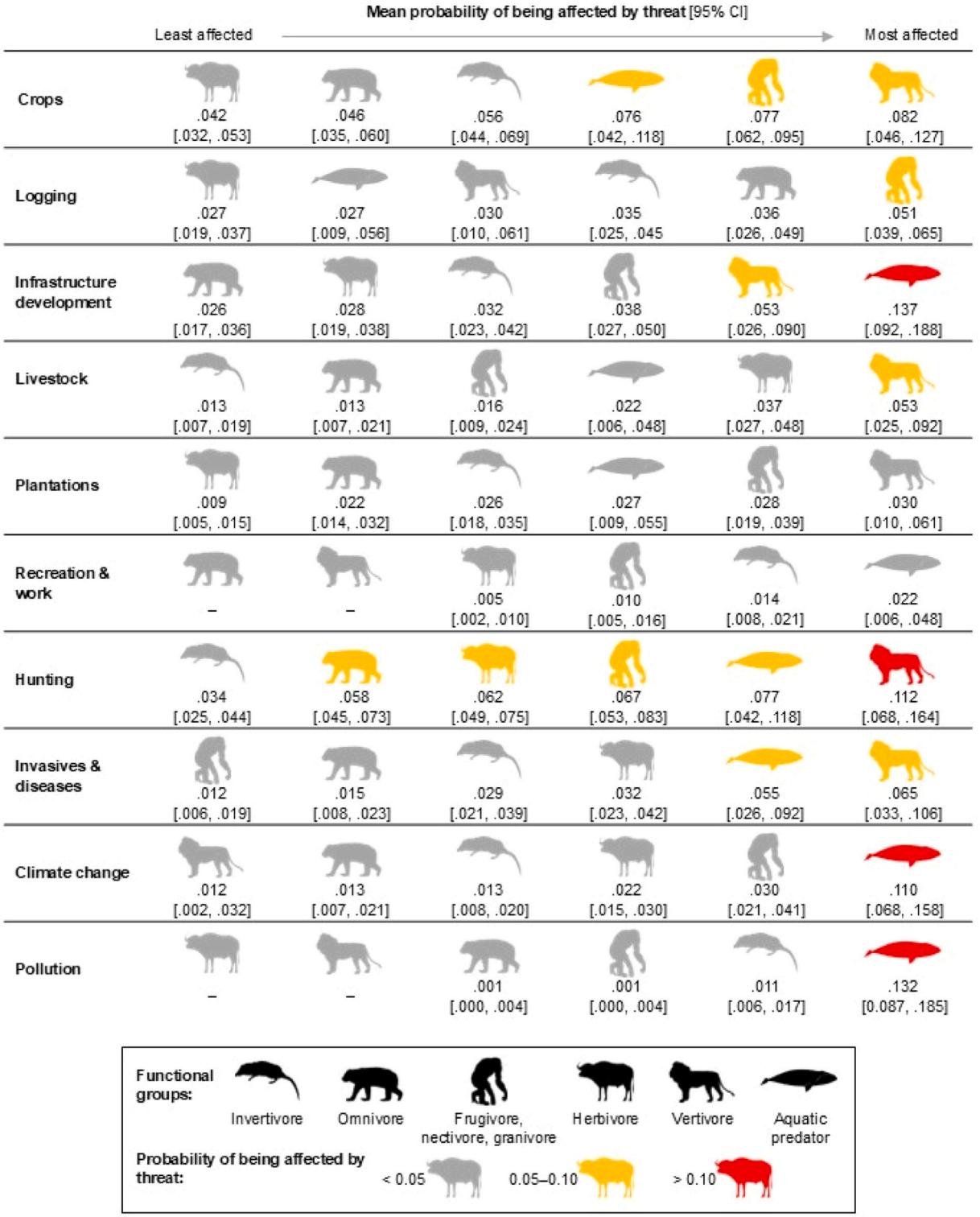

Fig. 3. Probability that a mammal species in each functional group is negatively impacted by each anthropogenic threat. Mean probability is shown with 95% credible intervals in brackets. Functional groups in the legend (black silhouettes) are arranged left to right from lowest to highest mean body mass. A dash indicates that no species in the functional group were affected by the threat. Silhouettes were obtained from Phylopic (www.phylopic.org).

Each functional group had a separate intercept representing the proportion of species in that functional group affected by the particular threat.

All analyses were carried out using Bayesian inference with the program JAGS and the *jagsUI* package in program R (Kellner, 2021; Plummer, 2003). We used weakly informative priors for the regression parameters (i.e., normal distributions with a mean of 0 and variance of 100). We ran three chains, each for 7000 interactions with a burn of 1000 iterations and thinning rate of 3 to obtain 6000 posterior samples. We assessed convergence by visually inspecting trace plots and assuring that the Gelman-Rubin statistic, R-hat < 1.1 for all parameters (Gelman, 2004).

3. Results

3.1. Anthropogenic threats to birds and mammals

An estimated 17% (1902 species) of 10,990 extant bird species are negatively impacted (i.e., medium and high threat impact scores) by at least one anthropogenic threat (Fig. 1). The top five anthropogenic threats affecting birds are: crops (9.0%, 990 species), logging (6.9%, 757 species), livestock (4%, 438 species), hunting (3.6%, 393 species), and invasives/diseases (3.3%, 361 species; Fig. 1). About 12% (605 species) of 5048 extant mammal species are negatively impacted by at least one anthropogenic threat. The top five threats affecting mammals are: hunting (5.7%, 287 species), crops (5.7%, 285 species), logging (3.6%, 182 species), infrastructure development (3.5%, 178 species), and invasives/diseases (2.5%, 128 species; Fig. 1).

Across all mammal and bird functional groups, an average of 68% ± 17% (mean ± SD) of the species that have medium or high threat impact scores are classified as endangered (i.e., IUCN status of critically endangered, endangered, or vulnerable; Appendix B). Near threatened species make up an additional ~20% of species affected by each threat, such that 89% ± 10% (mean ± SD) of species impacted are either endangered or near threatened.

3.2. Functional groups

Across anthropogenic threats, the most affected bird functional groups are vertivores, aquatic predators, frugivores, and

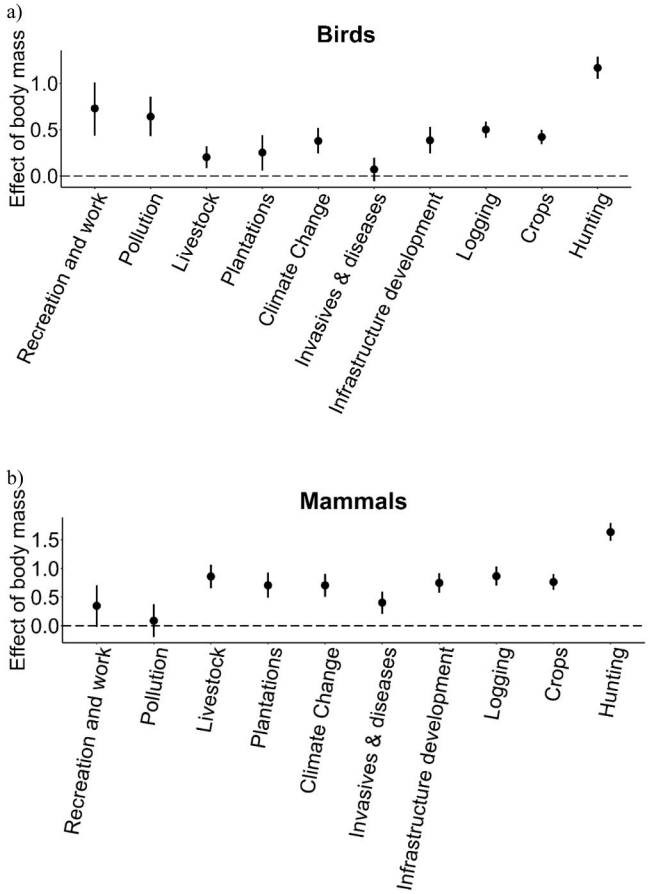

Fig. 4. Effect of body mass (on the logit scale) on the probability that a given (a) bird and (b) mammal species is impacted by each threat.

herbivores, with > 5% of the functional group affected by at least three anthropogenic threats (Fig. 2, Appendix C: Table C.1). Among all bird functional groups, vertivores are the group most impacted by crops, infrastructure development, and livestock. Aquatic predators are most impacted by invasives/diseases, climate change, and pollution. Frugivores are most impacted by logging, and herbivores by hunting. Though groups differ in the extent to which they are affected by crops, > 5% of species in all functional groups are negatively impacted by crops (Fig. 2). At least half of the functional groups have > 5% of species affected by both logging and hunting. Interestingly, aquatic predators are the only group to have > 5% of species affected by invasives/disease, climate change, and pollution. All bird functional groups have < 5% of species affected by plantations and recreation/work (Fig. 2).

For mammals, the functional groups most affected by anthropogenic threats are vertivores, followed by aquatic predators, and the frugivore/nectivore/granivore functional group, with > 5% of each functional group affected by at least three threats (Fig. 3, Appendix C: Table C.1). Among all functional groups, vertivores are most impacted by hunting, livestock, crops, and invasives/diseases. Aquatic predators are most impacted by pollution, climate change, and infrastructure development, and frugivore/nectivore/granivore species are most impacted by logging. Over half of the mammal functional groups have > 5% of species affected by both hunting and crops (Fig. 3). Aquatic predators are the only group to have > 5% of species affected by climate change and pollution. As with birds, all mammal functional groups have < 5% of species affected by plantations and recreation/work (Fig. 3). Sensitivity analyses revealed that imputing traits for species with missing data did not affect results (Appendix D: Figs. D.1 & D2).

In an analysis run using only threatened species (those categorized as critically endangered, endangered, or vulnerable), we found no differences for mammals (Appendix D: Fig. D.3). However, the most affected functional groups differ slightly for birds (Appendix D: Fig. D.4). In the analysis of all species (threatened and non-threatened), the group most impacted by crops, livestock, and plantations is vertivores, whereas in the analysis of threatened species it is granivores. These results suggest that threatened bird species may be affected by slightly different threats as compared to the overall species pool.

Interestingly, when using trophic levels instead of diet functional groups (i.e., all birds/mammals categorized as either a carnivore, herbivore, or omnivore), we found that carnivores and herbivores are impacted by threats much more frequently (70%, n = 10) than

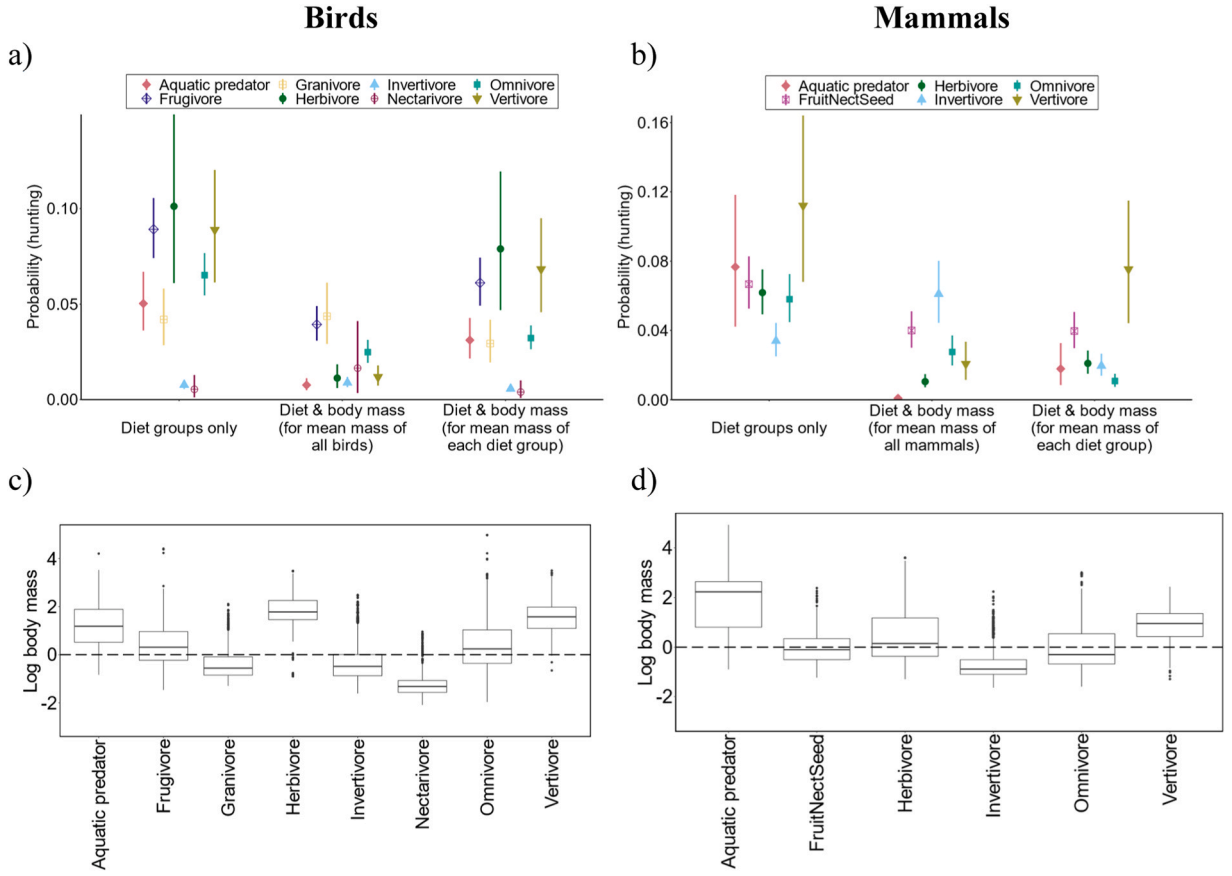

Fig. 5. Probability of being impacted by hunting across functional groups (a,b) and variation. in body mass across functional groups (c,d) for birds (a,c) and mammals (b,d). "Diet groups only" shows results obtained using functional groups as the only predictor in the model. "Diet & body mass" shows results obtained when both functional groups and body mass were used as predictors, with the probability of being impacted by hunting shown either for the mean body mass across all species or the mean body mass within each functional group. Log body mass values are shown on a standardized scale where zero is the mean across all bird (49 g) and mammal (166 g) species, respectively. FruitNectSeed refers to the frugivore/ nectarivore/ granivore mammal species.

omnivores for both birds and mammals (Appendix E).

3.3. Body mass

For both birds and mammals, body mass has a mean positive effect (17 of the 20 coefficients are above zero) on the probability that a species is impacted by a threat, meaning that larger species are generally more negatively impacted than smaller species across threats (Fig. 4). The effect of body mass is not significant for invasives/diseases for birds (posterior mean: 0.07 [95% CI: −0.06, 0.19]) or for pollution for mammals (posterior mean: 0.09 [95% CI: −0.2, 0.38]), suggesting that body size may not be quite as important factors for these threats.

Body size has the strongest effect on hunting for both mammals (posterior mean: 1.64 [95% CI: 1.48, 1.79]) and birds (posterior mean: 1.17 [95% CI: 1.05, 1.29]), with larger species being substantially more likely to be impacted by hunting than their smaller counterparts. Much (but not all) of the variation observed for hunting impacts among functional groups can be attributed to differences in body mass among groups, which is evident when comparing results from models that include only diet functional groups with those that also account for the effect of body size (Fig. 5a,b). For example, the probability of vertivore birds and mammals being impacted by hunting declines from 8.9% to 1.2% and 11.2–2.1% respectively, when body mass is included in the regression model, suggesting that body mass captures most of the variation that was previously attributed to differences based on diet. For birds, hunting has the largest impact on herbivores (posterior mean: 0.1 [95% CI: 0.06, 0.15]), frugivores (posterior mean: 0.09 [95% CI: 0.07, 0.11]), and vertivores (posterior mean: 0.09 [95% CI: 0.06, 0.12]), which are also some of the largest bird groups (Fig. 5a,c). However, aquatic predators and omnivores also have above average body size (Fig. 5c), but a bird that is an aquatic predator or omnivore is less likely to be at risk from hunting compared to a similarly sized herbivore, frugivore, or vertivore (Figs. 2 and 5a; diet & body mass model shown with mean mass for each diet group). For mammals, hunting has the largest impact on vertivores (posterior mean: 0.11 [95% CI: 0.07, 0.16]), and aquatic predators (posterior mean: 0.08 [95% CI: 0.04, 0.12]), which are also some of the largest mammal groups (Fig. 5b,d). Although aquatic predators have the largest average body size across mammal functional groups (Fig. 5d), a frugivore/nectivore/granivore or vertivore is more at risk from hunting compared to a similarly sized aquatic predator (Figs. 3 and 5b).

As with hunting, differences in body mass among functional groups explain some of the observed differences among groups for other anthropogenic threats, though many of the differences in threat impacts among functional groups and trophic levels cannot be attributed to differences in body mass alone (Appendix E & F).

4. Discussion

Our study provides critical information on which dietary functional groups are most affected by the top ten anthropogenic threats, and characterizes the extent to which a functional group's vulnerability to specific threats is attributable to variations in body size. For both birds and mammals, we found that negative impacts of anthropogenic threats are most common for frugivores (or frugivores/nectivores/granivores for mammals), vertivores (terrestrial vertebrate predators) and aquatic predators (Figs. 2 and 3). Predators perform important ecological functions, including consumption of prey and maintaining ecosystem structure through top down processes (Estes et al., 2011; Lacher et al., 2019). Predators also indirectly influence the behavior and population dynamics of prey species through perceived predation risk (Suraci et al., 2016; Zanette et al., 2011). Therefore, the loss of predators, which occupy high trophic levels, may have profound effects on broader ecosystems.

A recent study showed that herbivorous birds and mammals have higher extinction risk compared to carnivores and omnivores, though these broad trophic categories encompass many types of species, and using more specific diet categories revealed that piscivores, scavengers, frugivores, and consumers of general plant parts such as leaves were most threatened (Atwood et al., 2020). Along with our results, such analyses emphasize that ecosystems are at risk of losing critical functions due to common and widespread anthropogenic activities. However, when we analyzed our data using trophic levels (i.e., carnivore, herbivore, omnivore) instead of diet functional groups, we found that carnivores and herbivores are impacted by threats more than omnivores for both birds and mammals – in contrast to the results of Atwood et al. (2020) (Appendix E). Our results suggest that species with more specialized diets (i.e., non-omnivores) may be more impacted by anthropogenic threats regardless of whether their trophic position is high (i.e., carnivores) or low (i.e., herbivores).

Though all anthropogenic threats impact species from each functional group, threats varied in which functional groups are most impacted. For both birds and mammals, crops and livestock most affect vertivores, pollution and climate change most affect aquatic predators, and logging most affects frugivore birds or frugivore/granivore/nectarivores mammals (Fig. 2 & 3). For birds, hunting and invasives/disease most affect herbivores and aquatic predators, respectively, whereas for mammals these threats primarily affect vertivores (Figs. 2 and 3). Crops (i.e., annual and perennial non-timber crops) and livestock (i.e., ranching and livestock farming) are habitat-modifying threats that affect vertivores through habitat conversion and prey depletion and may facilitate other threats such as retaliatory killings due to livestock depredation (Baker et al., 2008; IUCN, 2024a; Kissui, 2008; Kissui et al., 2019). Vertivores are also affected by other threats associated with habitat loss and degradation, including logging (for birds) and infrastructure development, possibly via similar mechanisms. Aquatic predators are affected by pollution through direct mortality (e.g., oil spills) or indirectly by bioaccumulation and biomagnification (Gray, 2002; IUCN, 2024a; Treu et al., 2022). Climate change can result in the direct mortality of aquatic predators due to rising ocean temperatures, and indirectly through declines in reproductive success, changes in the distribution of prey due to increased melting of sea ice, severe weather patterns (e.g., storms), and increasing temperatures (IUCN, 2024a; Trathan et al., 2007). Additionally, climate change impacts are likely to cause cascading effects within ecosystems due to interactions between trophic levels (Zarnetske et al., 2012). Invasive species and diseases most affect aquatic predators (birds and mammals; Figs. 2

and 3) and vertivores (mammals; Fig. 3), suggesting that predators are threatened not only by habitat loss, pollution, and climate change, but also by hybridization with related species, competition or direct mortality from non-native species, and/or declines due to disease (Doherty et al., 2016; IUCN, 2024a; Lees et al., 2022).

In a related study, Leclerc et al. (2020) examined how threats affect taxonomic and functional diversity of insular endemic bird and mammal species at a global scale. They found that invertivore birds are most impacted by invasive species, vertivore birds are most impacted by pollution and human intrusions/disturbance, and frugivore/granivore/nectarivore mammals are most impacted by "wildlife exploitation" (biological resource use - hunting & logging) and "cultivation" (agriculture & aquaculture - crops, livestock, & plantations). In our analysis, we found that invertivore birds are most impacted by crops, vertivores birds by crops and logging, and frugivore/granivore/nectarivore mammals by crops, logging and hunting (Fig. 2 & 3). The contrasting results for birds between the two studies could be due to insular species being different than non-insular species or possibly differences in how threats are categorized. However, similar results for mammal species suggest that both insular and non-insular mammal species are affected by similar threats.

Frugivores are another functional group that provide crucial ecosystem services and are disproportionately affected by certain anthropogenic threats. Logging most impacts frugivore birds and frugivore/nectarivore/granivore mammals (Fig. 2 & 3). Our results are consistent with a meta-analysis on the effects of forest modification which found that, among bird functional groups, frugivores are the most negatively affected by forest conversion (Osuri et al., 2020). The loss of frugivore, granivore, and nectarivore species has potential ecological consequences in terms of seed dispersal, the composition and distribution of plants, and pollination (Lacher et al., 2019; Şekercioğlu et al., 2004). The negative effect of logging on frugivores is especially concerning given that frugivores can improve forest recovery through seed dispersal, provided there are frugivores left in the forest, which means logging threatens the very species that could help forests recover from logging (Bello et al., 2024). In addition to the effects of logging, frugivores, nectarivores, and granivores are also over-hunted compared to other bird and mammal groups, when accounting for body size (Fig. 5a,b). Generally, logging disproportionately impacts large-bodied species (Gutiérrez-Granados and Dirzo, 2021; Velho et al., 2012), and hunting is also strongly size-selective (Fig. 4). Thus, large-bodied frugivores are especially at risk from logging and hunting, with potentially devasting consequences for plants that depend on them for dispersion, and for global carbon storage more generally (Bello et al., 2024; Lim et al., 2020).

One reason anthropogenic threats disproportionately affect certain functional groups is because functional groups vary in body size, and larger species are more likely to be impacted across nearly all threats (Figs. 4 and 5). Hunting, in particular, is strongly size-selective for both birds and mammals, likely because human hunters target large-bodied species, but body mass also predicts impacts for other threats, including climate change. While climate change does not directly kill large-bodied species in the same way that hunting does, large-bodied species may be physiologically or demographically less able to cope with climate stress due to a smaller surface area to volume ratio, resulting in decreased body sizes (Gardner et al., 2011; Hantak et al., 2021; McCain and King, 2014; Smith et al., 1995).

Interestingly, we found a positive effect of body size for both birds and mammals across all five threats associated with habitat loss (crops, logging, livestock, plantations, and infrastructure development), in contrast to other studies that have suggested a greater risk of habitat loss for small-bodied species (Owens and Bennett, 2000; Ripple et al., 2017). While studies consistently show that large-bodied vertebrates are generally more threatened than small-bodied vertebrates (Atwood et al., 2020; Cardillo et al., 2005; Gaston and Blackburn, 1995; Ripple et al., 2017), additional research should evaluate the conditions under which small-bodied species may be vulnerable to specific threats, including habitat loss. The IUCN data we used aggregates threats across species ranges and thus may mask fine-scale variations, obscuring species' responses to threats at local scales.

In some cases, functional groups may be affected by threats primarily due to their body size. For example, herbivorous birds (mostly waterfowl and gamebirds), are likely hunted because they are large and consumed by humans rather than because they are herbivorous. Still, it is important to know that herbivorous birds are strongly impacted by hunting to evaluate how overhunting may affect ecosystem functions. In other cases, body mass does not fully explain differences among functional groups. Frugivorous birds and mammals, for example, are threatened by logging and hunting even though they are not the largest functional groups. Rather, other characteristics about these species, such as their habitat associations, make them vulnerable to certain threats.

Conservation implications

Global biodiversity is declining due to multiple anthropogenic threats, but each of these threats impacts different types of species, with consequences for functional diversity. For both birds and mammals, crop conversion and hunting affects many functional groups, especially vertivores and frugivores, while climate change and pollution have the strongest effects on aquatic predators, and logging has the biggest impacts on frugivores. Similar results between birds and mammals indicate that threats may impact functional diversity of birds and mammals in consistent ways. Our results highlight the need to target specific anthropogenic threats in order to conserve specific ecosystem functions. For both birds and mammals, habitat loss (e.g., crop conversion, logging) and hunting affect more functional groups than all other threats combined. Thus, global conservation efforts should focus on minimizing these threats that have the greatest impact on species and, consequently, ecosystem functioning.

CRediT authorship contribution statement

Sydney Ceyzyk: Writing – review & editing, Software, Data curation. **Zipkin Elise F:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Samuel Ayebare:** Writing – review & editing, Writing – original draft,

Software, Formal analysis, Conceptualization. **Peter J Williams:** Writing – review & editing, Software, Project administration, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2026.e04292.

Data availability

All code and data are available on GitHub (https://github.com/Samwiry/Ayebare_et_al_2026) and Zenodo (F).

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