

# Drivers of extinction risks and shortfalls across terrestrial vertebrates in the Philippine global biodiversity hotspot

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## Research Article

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# Abstract

The Philippines is a biodiversity hotspot with a rich variety of terrestrial vertebrate species, many of which are endemic and under threat from environmental changes and unsustainable activities. Effective conservation action is urgently needed; however, progress is hampered by persistent knowledge shortfalls and uneven research efforts. In this study, we assessed the extinction risks, threats, and knowledge gaps of 1,258 Philippine terrestrial vertebrate species. We found that at least 15%–23% of the species are at risk of extinction, particularly endemic amphibians and mammals, primarily driven by habitat loss and overexploitation. However, reptiles remain markedly underrepresented in research and their true threat status is likely underestimated. Our findings highlight historical research biases that continue to perpetuate conservation inequities, leaving vulnerable and data-deficient species and areas overlooked. Filling these gaps with balanced research investment, expanded monitoring, and better data sharing is crucial for informed conservation. We recommend using integrative tools and remote sensing to tackle major biodiversity shortfalls in the Philippines. Integrating collaboration, citizen science, targeted surveys, and genetic research can address these data gaps. Our study offers a strategic framework for guiding national conservation priorities and safeguarding the country's rapidly vanishing wildlife heritage, emphasizing that, without informed action, the Philippines risks losing its unique biodiversity.

## Highlights

- The Philippines is a major global biodiversity hotspot.
- At least 15-23% of Philippine terrestrial vertebrates are at a risk of extinction.
- Larger endemic species with limited habitat breadth are at a higher risk.
- Threatened species have been poorly studied and recorded.
- Low research effort is allocated to endemic species but is well recorded in GBIF.
- Significant spatial bias in research effort and species observation was observed.

## 1. Introduction

The world is currently experiencing a global biodiversity crisis, with species extinction rates estimated to be 1,000 times higher than natural background rates, primarily because of human activities combined with stochastic events (Ceballos and Ehrlich 2002; Cowie et al. 2022; Theobald et al. 2025). This extinction crisis threatens ecosystem stability and the essential services biodiversity provides to human societies (Li et al. 2017; Farley et al. 2024; Keck et al. 2025). Global scientists, policymakers, and different stakeholders set the Kunming-Montreal Global Biodiversity Framework (GBF), adopted in December 2022 at the UN Biodiversity Conference (COP15), which aims to halt and reverse biodiversity loss by 2030 and set the world on a path to living in harmony with nature by 2050 (Convention on Biological Diversity 2022; Hughes and Grumbine 2023).

The Philippines' unique biogeographical history, shaped by geological processes such as plate tectonics and sea-level fluctuations, has contributed to high species endemism (Heaney 1986; Heaney et al. 2016). Situated within the Coral Triangle and Indo-Malayan biodiversity hotspot, the archipelago harbours more than 52,000 described species, with a significant proportion found nowhere else on Earth (Gaither and Rocha 2013; Rowsey et al. 2022; Goulding and Dayrat 2023). As one of the world's 17 megadiverse nations, it plays a crucial role in global conservation efforts, holding an extraordinary array of biodiversity with high levels of endemism across its terrestrial and marine ecosystems (Myers et al. 2000; Alcala 2004; Ceballos and Ehrlich 2006). For instance, over 60% of vertebrate species are endemic to the country (Gonzalez et al. 2018). However, despite its conservation significance, Philippine biodiversity faces a wide range of threats to species and habitats (Posa et al. 2008; Ortiz and Torres 2020; Agduma et al. 2023). Deforestation owed to agricultural expansion, logging, and infrastructure development has led to the fragmentation of pristine habitats (Kummer and Sham 1994; Posa et al. 2008; Ortiz and Torres 2020). Illegal wildlife trade, poaching, and unsustainable wildlife hunting practices further exacerbate biodiversity declines (Scheffers et al. 2012; Brandis et al. 2023). Moreover, climate change poses additional risks, altering habitat conditions and increasing the frequency of extreme weather events, which negatively impacts species distribution and ecosystem resilience (Pulhin and Lasco 2010; Alcala et al. 2012; Pang et al. 2021). As various threats to Philippine biodiversity grow, ongoing scientific research is vital for understanding species distribution, ecological interactions, and conservation.

Understanding biodiversity loss is crucial for creating conservation strategies and sustainably managing resources, especially in developing economies (Rodrigues et al. 2014; Doi and Takahara 2016; Hughes 2017; Caldwell et al. 2024). A key aspect of this understanding is recognising that species vary in their vulnerability to extinction (Rodrigues et al. 2014; Atwood et al. 2020; Harfoot et al. 2021; Chichorro et al. 2022). Although the primary drivers of biodiversity decline, such as habitat destruction, overexploitation, pollution, invasive species, and climate change, are well established (Bonebrake et al. 2019; Harfoot et al. 2021; Borgelt et al. 2022), the way individuals respond to these threats depends on their unique biological and ecological traits. Life-history traits such as reproductive rate, body size, dispersal ability, and ecological specialisation, are among the most important correlates of species extinction risk (Collen et al. 2011; Pearson et al. 2014; Gallagher et al. 2021; Chichorro et al. 2022). For example, species with slow reproduction, long lifespans, or specialised habitat requirements are often less resilient to environmental disturbances than those with high reproductive outputs and broader ecological tolerances (Chichorro et al. 2022).

In the Philippine context, where many endemic species have evolved in isolated and narrow habitats, analysing life-history traits is essential for identifying the most vulnerable taxa. For instance, the Philippine Eagle (*Pithecophaga jefferyi*) has a slow reproductive rate and depends on large contiguous forests, making it highly susceptible to deforestation and human disturbance (Abaño et al. 2015; Ibanez et al. 2016; Sutton et al. 2023). Similarly, Tamaraw (*Bubalus mindorensis*), with its restricted range in Mindoro's grasslands and forests, faces critical threats from habitat loss and hunting (Bonenfant et al. 2023; Enrico Buebos-Esteve et al. 2024). By assessing how life-history traits interact with external pressures, conservation biologists can better predict which species are at the greatest risk and develop

appropriate conservation measures (Chichorro et al. 2019, 2022; Atwood et al. 2020). Incorporating species life-history traits into extinction risk assessments is widely practiced and particularly relevant for conservation planning in the Philippines, where limited resources to implement conservation interventions necessitate strategic prioritisation.

Although global and continental conservation priorities shape regional policies, national efforts are crucial because they address local ecological, social, and cultural realities (Tanalgo and Hughes 2018, 2019; Gamalo et al. 2021; Dela Cruz et al. 2023; Caldwell et al. 2024). Setting national priorities and strategies can focus on specific threats, protecting unique species, and integrating local knowledge and governance (Failing et al. 2007; Gonzalez et al. 2018; Tanalgo and Hughes 2019; Zhu et al. 2021). By considering challenges such as land use, resources, and community involvement, national conservation plans can help turn global goals into practical actions and create more effective and sustainable outcomes by balancing global priorities with local needs. National and regional assessments of the conservation status of Philippine wildlife (Gonzalez et al. 2018) and studies aimed at understanding the knowledge shortfalls for some taxonomic groups, including bats (Tanalgo and Hughes 2018), primates (Gamalo et al. 2021), carnivores (Fernandez et al. 2025), birds (Kittelberger et al. 2021; Dela Cruz et al. 2023), and herpetiles (Abdullah et al. 2023), yet a consolidated Philippine-wide assessment remains lacking.

A trait-based approach is used to enhance threat assessments, guide species recovery, and inform habitat restoration efforts (Gallagher et al. 2021; Zhong (钟) et al. 2022; Coutinho et al. 2023; Deschênes et al. 2024). As biodiversity continues to decline, a deeper analysis of life-history traits is indispensable for safeguarding the unique yet fragile wildlife biodiversity in the Philippines. However, our knowledge of biodiversity is unevenly spread and is often constrained by knowledge shortfalls, as many Philippine species remain understudied in taxonomic groups (Abdullah et al. 2023; Hilario-Husain et al. 2024). This imbalance distorts biodiversity understanding in the Philippines, influences policy, and directs research and conservation resources (Buechley et al., 2019; Dela Cruz et al., 2023; Tanalgo et al., 2023).

We examined extinction risk patterns in Philippine terrestrial vertebrates using life-history traits, ecological status, and knowledge shortfall proxies. Body size, trophic level, habitat breadth, and IUCN threat level are well-established predictors of risk (Chichorro et al. 2022), and we evaluated whether these trends hold for the Philippine species. We posit that larger-bodied species face higher risks owing to slower reproduction, greater resource needs, and vulnerability to hunting and habitat loss (Collen et al. 2011; Ducatez and Shine 2017), with large herbivores being especially susceptible (Atwood et al. 2020). Herbivores are also disproportionately impacted by hunting and habitat conversion in tropical regions (Benítez-López et al., 2019, 2019; Scheffers et al., 2012; Tanalgo et al., 2023). Lastly, we assume that species with narrow habitat breadth increase risk by limiting their adaptability to environmental changes (Swihart et al. 2003).

We posit that research efforts are biased toward larger-bodied species, certain trophic groups, wider-ranging or non-endemic species, earlier-described species, and those with more documented threats.

Research efforts may also differ based on extinction risk, either intensifying because of conservation urgency or declining because of species rarity (Chen et al. 2019; Shuai et al. 2024). We further assessed whether species occurrence within protected areas differed according to conservation status. Higher-risk species may have more records in protected areas due to targeted conservation or restricted ranges, whereas non-threatened species may be more evenly distributed.

## 2. Materials and methods

We utilised the latest version of the IUCN Red List database (2024-2), one of the most authoritative and widely used global resources for assessing species extinction risk, to compile a comprehensive species database for all Philippine terrestrial vertebrates including amphibians, reptiles, birds, and mammals (IUCN Red List 2025). We included only species classified under 'terrestrial' systems and inland freshwater habitats, excluding domesticated species. The final analysis included 1,258 species. We used the chi-square test of association ( $\chi^2$ ) to determine significant relationship between conservation status, endemism, and families within classes.

We classified the species based on their taxonomic groups, endemism, and conservation status. We collated species life-history traits from AmphiBIO for amphibians (Oliveira et al. 2017), RepTraits for reptiles (Oskyrko et al. 2024), AVONET for birds (Tobias et al. 2022) and Phylacine 1.2 for mammals (Faurby et al. 2018). We defined endemism as a species occurring in a single geopolitical region based on IUCN red list data.

Prior to the analysis, necessary data treatments and tests were conducted, and each model was examined to ensure that there was no overdispersal. We implemented all our analysis and modelling in the open statistical software, Jamovi (v 2.6.) (The jamovi project 2024). Data visualisation was performed using GraphPad Prism (GraphPad Prism 2022) and SciMago Graphica (Hassan-Montero et al. 2022). All spatial analyses and treatments were performed using Quantum GIS (v. 3.32) (QGIS Development Team 2025).

### 2.1. Extinction risk analysis

We estimated the extinction risk potential of all vertebrate species as well as for each of the four taxonomic groups, following the approaches of Richman et al. (2015) and Tanalgo et al. (2022). To examine the relationship between extinction risk and life-history traits, we transformed the conservation status into an ordinal numerical scale ranging from 0 to 4 (0 = Least Concern, 1 = Near Threatened, 2 = Vulnerable, 3 = Endangered, and 4 = Critically Endangered), assuming a linear increase in extinction risk across categories (Ducatez and Shine 2017; Kittelberger et al. 2021). Species classified as Data Deficient (DD) were excluded from analysis. We included body mass, body size (for amphibians), trophic level, and habitat breadth, which are common and almost complete for all taxonomic groups, as explanatory variables. We  $\log_{10}$ -transformed the body mass and size prior to the analysis. Trophic levels were classified to "herbivores", "carnivores", and "omnivores" based on Atwood et al. (2020) based on

diet extent from respective databases. Habitat breadth was calculated based on the number of major habitats occupied by the species (Etard et al., 2020; Tanalgo et al., 2023). For taxa lacking trait data, we averaged the values at the genus level. We added the number of threats and studies as predictors, assuming that species with a higher number of threats but a lower number of studies tend to be more at risk of extinction. All explanatory variables were z-transformed to standardise their scales and enable comparison of effect sizes. We initially fitted generalised linear mixed models (GLMMs) for each taxonomic group with a negative binomial error structure, accounting for integer values and zero-inflated data of extinction risks. We incorporated families (nested within order) as a random effect to account for phylogenetic relatedness in the extinction risk. As taxonomic families accounted for significant variation only in birds, we used generalised linear mixed models (GLMMs) for this group and generalised linear models (GLMs) for amphibians, reptiles, and mammals in our final analysis.

## 2.2. Assessing threat patterns

We identified threatening processes based on the IUCN Red List data and reclassified them into four broad categories: habitat alteration/destruction, invasive species (including diseases), climate change, and overexploitation (Ducatez and Shine 2017). We then assessed whether these threatening processes were randomly distributed across families and endemism within each class, using a chi-square test of association ( $\chi^2$ ).

## 2.3. Predicting knowledge shortfalls for Philippine terrestrial vertebrates

We hypothesized that the frequency of species studies is related to species extinction risk. We used the number of studies per species as a proxy for 'knowledge shortfall' (Tanalgo and Hughes 2018; Feijó et al. 2019; Preble et al. 2021; Shuai et al. 2024), based on the assumption that studies on species are more likely to receive more effort and conservation interventions. Due to institutional limitations, we used Google Scholar (<https://scholar.google.com.ph/>) to quantify the studies per species. It is open access, does not require institutional login, and offers broader coverage, including studies not in Scopus and Web of Science, likely covering local Philippine journals. To reduce bias, we used the incognito mode of our web browser and searched using a consistent syntax ["species X" + "Philippines"] to retrieve all publications containing the species name for each species included in the analysis (e.g., "*Pteropus vampyrus*" + "Philippines"). We included studies from 1950 to the present, and then limited our search to the English language, as it is the *lingua franca* in the Philippines for scientific writing and publishing in the natural sciences.

We also included the number of species occurrence records in the Philippines available at the Global Biodiversity Information Facility (GBIF) (1990–2024) as an additional proxy for knowledge shortfalls. Species with few GBIF occurrence records are likely to be underrepresented in research, monitoring, and conservation assessments. This may have resulted from limited field studies, taxonomic uncertainties, or data accessibility issues contributing to the knowledge gaps. In contrast, species with more records have also been studied. Individual species occurrence records were manually searched in the Global

Biodiversity Information Facility (GBIF) database between March 20 and April 3, 2025. All available records were included and entries with dubious species names or questionable locations were carefully removed. Using QGIS, we further cleaned the dataset by removing duplicate records and occurrences outside terrestrial boundaries of the Philippines.

We applied the Kendall's  $\tau$ -b to assess congruence between the number of studies and GBIF occurrence records, and Kruskal-Wallis test to assess significant differences in study frequency and GBIF occurrence records among taxonomic groups. Additionally, we assessed potential biases in research allocation and data availability and quantified the distribution evenness of both research efforts (publication counts) and GBIF occurrence records across taxonomic groups (i.e., measured at the family level) and IUCN conservation categories using Pielou's evenness. The values range from 0 (complete inequality, where one category dominates) to 1 (perfect evenness across all categories). We compared the Google Scholar mention and GBIF occurrence records according to the threatened category using the Mann–Whitney  $U$  test.

To examine the relationship between the number of studies, GBIF records, and species natural history traits, we fitted generalised linear mixed models (GLMMs) for each taxonomic group using a negative binomial error structure to accommodate count data and account for zero inflation. The explanatory variables included body mass, body size, habitat breadth, trophic level, number of threats, and the year of discovery. Family (nested within order) was included as a random effect to account for phylogenetic relatedness. For groups where family level variation was negligible, we used generalised linear models (GLMs).

## 2.4. Spatial patterns of knowledge shortfalls

Using QGIS, we assessed the overlap in species distributions across taxonomic groups at the provincial level. We then examined the congruence between species richness and the number of occurrence records across groups using the Spearman's rank correlation test.

We digitised and processed to construct  $0.1^\circ \times 0.1^\circ$  (approximately 10 km<sup>2</sup>) grid maps, where each cell represents the sum of the frequency of occurrence records and unique species occurring within the spatial grid. To assess the spatial clustering of species occurrences, we computed univariate local Moran's  $I$  using GeoDa v1.22 (Anselin et al. 2022). Moran's  $I$  value range from  $-1$  (dispersed) to  $1$  (clustered), with values near  $0$  indicating a random distribution of species occurrence. Furthermore, to identify potential research hotspots, we applied \*Getis-Ord  $G_i^*$  statistics, which evaluate the local spatial association of species richness by comparing each grid cell's species count with that of its neighbouring cells (Kuletz et al. 2015; Sussman et al. 2019). This approach detects statistically significant clusters of high species richness (hotspots) and low species richness (coldspots) by assessing their deviations from the global spatial mean (Li et al. 2017).

## 2.5. Species distribution within protected areas

The cleaned occurrence records were then overlaid onto the Philippine protected area boundaries, which were obtained from the Global Protected Planet database, to assess the spatial distribution of species records in relation to protected areas (UNEP-WCMC and IUCN 2025). We computed the percentage of species and occurrence records that overlapped with the PAs.

## 3. Results

### 3.1. Diversity and conservation status

We analysed the extinction risk and knowledge shortfalls for 1,258 species of Philippine terrestrial vertebrates, comprising 114 amphibians (9%), 323 reptiles (26%), 615 birds (49%), and 206 mammals (16%). Among these groups, amphibians had the highest proportion of species classified as threatened (i.e., Vulnerable, Endangered, or Critically Endangered) at 24%, followed by mammals (19%), birds (16%), and reptiles (9%) (Fig. 1a). A significant relationship between family and conservation status was only found in reptiles ( $c^2 = 164.108$ ,  $df = 95$ ,  $p < .0001$ ) and mammals ( $c^2 = 276.393$ ,  $df = 125$ ,  $p < .0001$ ). In terms of endemism, we observed a significant association between family and endemism across all taxonomic groups ( $p < 0.001$  for all groups). Similarly, amphibians exhibited the highest level of endemism (83%), followed by reptiles (78%), mammals (65%), and birds (39%) (Fig. 1b; **Supplementary Data S1**).

### 3.2. Determinants of extinction risk

Our analysis estimated an overall extinction risk proportion of 16% (95% CI: 15–23%) for Philippine terrestrial vertebrates, with considerable variation across taxonomic groups. This overall risk is lower than extinction risk estimates reported for Southeast Asia ( $\hat{p}_{\text{extinction}} = 18\%$ ; 95% CI: 16–17%) and the broader Asian continent ( $\hat{p}_{\text{extinction}} = 21\%$ ; 95% CI: 19–29%). Among Philippine taxa, amphibians exhibited the highest extinction risk, with an estimated extinction risk of 25% (95% CI: 24–30%), a level comparable to that of amphibian species in Southeast Asia. Mammals followed, with an extinction risk of 23% (95% CI: 19–36%), both notably higher than those observed in other groups and exceeding the regional and continental estimated extinction risks in Asia and Southeast Asia (Fig. 2).

The determinants of extinction risk varied across the taxonomic groups (Fig. 3). Habitat breadth emerged as the most consistent predictor across all groups, with narrower habitat ranges strongly associated with higher extinction risk. This relationship was most evident in birds ( $\beta = -0.657$ ,  $p = 0.005$ ) and reptiles ( $\beta = -0.657$ ,  $p = 0.01$ ), followed by amphibians ( $\beta = -0.635$ ,  $p = 0.02$ ) and mammals ( $\beta = -0.298$ ,  $p = 0.02$ ). Body mass showed a significant positive association with extinction risk exclusively in mammals ( $\beta = 0.639$ ,  $p < 0.0001$ ), suggesting that larger-bodied mammal species face greater vulnerability than smaller-bodied groups. The trophic level was only significant for birds, where herbivorous species demonstrated an elevated risk compared to other trophic groups ( $\beta = 0.464$ ,  $p = 0.022$ ). The cumulative number of threats significantly increased the extinction risk for reptiles ( $\beta = 0.710$ ,  $p = 0.0003$ ), birds ( $\beta = 1.185$ ,  $p < 0.0001$ ), and mammals ( $\beta = 0.426$ ,  $p = 0.0003$ ), but not for

amphibians. Research efforts, as measured by publication frequency, showed significant associations with better-studied bird ( $\beta = -0.993$ ,  $p < 0.0001$ ) and mammal ( $\beta = -0.305$ ,  $p = 0.027$ ) species, demonstrating lower extinction risk estimates (Fig. 2; **Supplementary Data S3**).

### 3.3. Patterns of threats

Our analysis revealed a significant variation in threat distribution across taxonomic classes ( $p < 0.001$  for all threats, except amphibian families) (Fig. 47). Habitat alteration and overexploitation have emerged as the most pervasive threats, affecting 87% and 77% of amphibian species, respectively, although these patterns showed no significant relationship at the family level for amphibians. Reptiles and mammals demonstrated similar vulnerability to habitat alteration (> 50% of species affected), substantially higher than birds (37%), whereas overexploitation affected mammals (52%) and reptiles (47%) more severely than birds (27%). Invasive species showed a particular impact on amphibians (7% of species affected), whereas climate change remained the least known threat across all groups (1–3%). Notably, endemic species face heightened risks, with habitat alteration threatening 90% of endemic amphibians and 48% of endemic birds, and overexploitation affecting 80% of endemic amphibians, 56% of endemic mammals, and 49% of both endemic birds and reptiles. Climate change had a significant impact only on endemic birds (12%), highlighting the disproportionate vulnerability of endemic species to multiple concurrent threats.

### 3.4. Distribution and Determinants of Research Efforts

Research effort differed significantly across taxonomic groups (Kruskal-Wallis:  $H = 146.760$ ,  $df = 3$ ,  $p < 0.0001$ ), with mammals being the most studied (Fig. 5a-d). Non-threatened species have consistently received greater research attention than threatened species have. Among the threatened groups, amphibians were the least studied (mean = 15.97, median = 13.50; Mann-Whitney  $U = 549$ ,  $p < 0.0001$ ), followed by reptiles (mean = 26.25, median = 7;  $U = 5349$ ,  $p < 0.0001$ ), birds (mean = 52.99, median = 25;  $U = 17107$ ,  $p < 0.0001$ ), and mammals (mean = 110.03, median = 26;  $U = 3394.5$ ,  $p = 0.0004$ ).

Likewise, GBIF records varied significantly across taxonomic groups (Kruskal-Wallis:  $H = 226.021$ ,  $p < 0.0001$  (Fig. 5e-h). Threatened species had fewer occurrence records than non-threatened species, with reptiles being the least recorded (mean = 21.71, median = 7;  $U = 3575$ ,  $p < 0.0001$ ), in contrast to amphibians (mean = 89.21, median = 35;  $U = 523.5$ ,  $p < 0.0001$ ), mammals (mean = 79.01, median = 16.50;  $U = 2174$ ,  $p < 0.0001$ ) and birds (mean = 333.36, median = 150;  $U = 14418$ ,  $p < 0.0001$ ). A weak but significant congruence was detected between the research effort and the GBIF records (**Supplementary Data S2**).

A comparison of Pielou's evenness index across taxonomic groups revealed clear biases in both research allocation and observation efforts. In terms of the number of studies, uneven distributions were observed across all "Endangered" groups, except for birds. Remarkably, "Critically Endangered" reptiles and amphibians, "Least Concern" mammals, and "Near Threatened" birds have exhibited a particularly uneven number of studies. A similar pattern emerged in GBIF occurrence records, where unevenness

closely mirrored that of research efforts and notable disparities across taxonomic groups and conservation status categories (Fig. 6).

Taxonomic families have significantly influenced research efforts. Generalised linear mixed models (GLMMs) revealed that larger body size, broader habitat breadth, and earlier description year were consistently associated with higher study numbers across all groups. Non-endemic species have received increasing attention among birds, amphibians, and reptiles. Trophic level also played a role, with herbivorous reptiles being more frequently studied (Fig. 7a-d; **Supplementary Data S4**).

In contrast, taxonomic families did not explain the GBIF record variation in amphibians and mammals; therefore, generalised linear models (GLMs) were applied. Body size was significant only for smaller birds and mammals, whereas habitat breadth was important for amphibians, reptiles, and mammals. Unlike research efforts, endemic species have more GBIF records among amphibians, birds, and mammals. Herbivory was significant only for mammals, and birds facing fewer threats had more records. Earlier description dates correlated with higher GBIF records across all groups (Fig. 7d-h; **Supplementary Data S5**).

### 3.5. Spatial patterns of knowledge shortfalls

We observed substantial taxonomic and geographic variations in the GBIF occurrence records. At the provincial scale, there was significant congruence between species richness and the number of occurrence records, with particularly strong correlations between amphibians and reptiles (Fig. 8). Our analysis further showed significant disparities in representation between species of different conservation statuses, with the least threatened species dominating the records, whereas threatened species were noticeably underrepresented. Moran's  $I$  value indicate varying degrees of positive spatial autocorrelation for all taxonomic groups. Birds ( $I = 0.335$ ) and amphibians ( $I = 0.287$ ) showed moderate to strong clustering of similar values, whereas mammals ( $I = 0.159$ ) and reptiles ( $I = 0.153$ ) showed weak spatial clustering, with values distributed more randomly across space. Notably, birds had the highest proportion of hotspot grids (4% of the 3,716  $10 \times 10$  km<sup>2</sup> grids) compared with the other groups.

In protected areas, most taxonomic groups were adequately represented in terms of species richness, exceeding 90%, except for reptiles, which had only 71% of the species recorded in these regions. Regarding the extent of protected area (PA) coverage for occurrence records, mammals were best represented with 38% of their records within PAs. This was followed by amphibians (35%), birds (31%), and reptiles, which had the lowest coverage at 27%. The proportion of occurrence records for threatened species within protected areas was moderately high; however, there was significantly less coverage for amphibians and reptiles (Table 1). Conversely, at least 47% of the occurrence records for data-deficient mammal species overlapped with protected areas.

Table 1

Percentage of GBIF occurrence records for terrestrial vertebrates in the Philippines within Protected Areas categorised by conservation status.

Conservation Status	Amphibians	Reptiles	Birds	Mammals
Data Deficient	26.64	26.59	0.00	46.66
Least Concern	31.81	26.52	30.55	37.34
Near Threatened	49.65	36.33	47.59	36.48
Vulnerable	49.01	30.55	49.30	44.70
Endangered	0.00	22.67	25.96	31.19
Critically Endangered	0.00	28.95	41.52	30.85

## 4. Discussion

### 4.1. Overview of diversity and conservation of Philippine terrestrial vertebrates

We analysed 1,258 Philippine terrestrial vertebrates and found significant variations in patterns of diversity, endemism, extinction risk, and knowledge shortfalls. Amphibians were the most threatened, with 24% of the species threatened, followed by mammals, birds, and reptiles. This pattern aligns with global trends, where amphibians face heightened risks due to habitat loss, disease, and climate sensitivity (Nori et al. 2015; Catenazzi 2015). The significant association between mammalian and reptilian families and conservation status suggests that extinction risk is not randomly distributed but may instead be linked to phylogenetic and ecological traits. For mammals, large-bodied species (e.g., Philippine deer *Rusa marianna* and Philippine warty pig *Sus philippensis*) and range-restricted endemics (e.g., cloud rats and endemic flying foxes) face a disproportionate number of threats (Heaney 1986; Heaney et al. 2016). Similarly, among reptiles, certain families with specialised habitat requirements (e.g., forest-dependent skinks and endemic snakes) showed elevated vulnerability compared with more adaptable, widespread species (e.g., common house geckos) (Diesmos et al. 2002; Alcalá et al. 2012).

Endemism was strikingly high across all groups, apparently reflecting the country's archipelagic nature, which promotes speciation through geographic isolation. Endemism was particularly high among 83% of amphibians, 78% of reptiles, and 65% of mammals, reinforcing the Philippines' status as a biodiversity hotspot for these groups (Heaney 1986; Diesmos et al. 2002, 2015). Birds exhibited the lowest endemism (39%), likely because of their higher dispersal capacity. However, they still represent a substantial portion of the country's unique wildlife (Ducatez and Shine 2017; Kittelberger et al. 2021; Chichorro et al. 2022).

### 4.2. What drives species to the brink?

Our analysis revealed significant patterns in extinction risk among Philippine terrestrial vertebrates, highlighting both shared and taxon-specific vulnerability. The 16% extinction risk for Philippine terrestrial vertebrates, although slightly lower than the Southeast Asian (18%) and broader Asian (21%) averages, revealed critical taxonomic disparities that warrant concern. Notably, amphibians (25% risk) and mammals (23% risk) have emerged as particularly vulnerable groups, with their risk levels exceeding regional averages, which is likely related to their narrow habitat breadth, greater exposure to habitat alterations, and rapid environmental changes (Brooks et al. 1999; Corlett 2007; Posa et al. 2008; Rowley et al. 2009; Bickford et al. 2010). In contrast, birds and reptiles may exhibit slightly lower overall risk owing to greater dispersal capabilities (in birds) and broader habitat tolerances (in some reptiles), although certain species within these groups are highly susceptible to threats (Doherty et al. 2020; Sheard et al. 2020; Kittelberger et al. 2021; Alzate and Onstein 2022; Cervantes-López and Morante-Filho 2024)..

### **4.3. Charting the loss: Extinction pattern across Philippine terrestrial vertebrates**

The observed variations in threat susceptibility and differential influence of ecological traits provide important insights into the potential mechanisms driving species persistence and decline in the Philippines (Ducatez and Shine 2017; Chichorro et al. 2022). The elevated extinction risk in amphibians and mammals compared with birds and reptiles is likely due to their distinct ecological and biological characteristics.

Amphibians are highly sensitive to environmental changes owing to their permeable skin, biphasic life cycles (aquatic larvae and terrestrial adults), and narrow microhabitat requirements (Catenazzi 2015; Pottier et al. 2025). Their dependence on aquatic and terrestrial habitats makes them more vulnerable to habitat alterations and pollution (Kerby et al. 2010; Nowakowski et al. 2017). Additionally, emerging diseases, such as chytridiomycosis, threaten amphibian populations globally, which may also contribute to their high risk in the Philippines (Swei et al. 2011). However, in our model, only habitat breadth significantly affected extinction risks.

Body mass was the only significant associated among mammals, with larger species exhibiting a higher extinction risk, consistent with previous global investigations (Atwood et al., 2020; Ripple et al., 2017; Tanalgo et al., 2023). Mammals, particularly larger-bodied species, face heightened extinction risks due to their lower population densities, slower reproductive rates, and greater habitat and resource requirements (Ripple et al. 2014; Turvey 2018; Atwood et al. 2020). Larger mammals typically require expansive home ranges, which makes them particularly susceptible to habitat fragmentation (Kuipers et al. 2021). They are also disproportionately targeted by hunting and wildlife trade, both of which are major drivers of the decline in the Philippines (Corlett 2007; Ripple et al. 2016). For example, among bats in the Philippines, larger species, such as flying foxes (genera *Acerodon* and *Pteropus*), are at greater risk of extinction than their smaller counterparts (Mildenstein et al. 2005; Tanalgo and Hughes 2018). This heightened vulnerability is often linked to factors such as reliance on intact forest habitats, slower

reproductive rates, increased susceptibility to hunting, and habitat loss (Tanalgo et al., 2023; Tanalgo and Hughes, 2019).

Among the ecological traits examined, a narrower habitat breadth emerged as the most consistent predictor of extinction risk, a pattern especially pronounced in island ecosystems, where species are often confined to small, isolated habitats (Kier et al. 2009; Shipley and McGuire 2024). Many Philippine species are single-island endemics with extremely limited ranges, such as the Philippine tarsier in Bohol (Brown et al. 2014), the Critically Endangered Cebu flowerpecker, and the Negros Bleeding Heart Pigeon (Mynott et al., 2021), making them inherently vulnerable because of small population sizes and low genetic diversity (Dutson et al. 1993). Our observed pattern underscores how ecological specialisation increases vulnerability; for example, species with narrow habitat ranges (e.g., forest-dependent endemics) are likely to have lower local abundance and are far more likely to decline when their habitats are degraded or fragmented (Swihart et al. 2003; Corlett 2007; Jenkins et al. 2013; Keinath et al. 2017). An extensive comparative analysis by (Chichorro et al. 2022) demonstrated that habitat breadth consistently emerged as one of the strongest and most universal predictors of extinction risk across diverse life forms, including vertebrates.

Contrary to our expectations, only herbivorous birds, including frugivores and nectarivores, demonstrated heightened susceptibility to extinction compared with other taxonomic groups. Herbivorous birds heavily rely on primary forest resources for foraging and other life histories, like the iconic Philippine hornbills are tightly linked to mature forest trees that are vanishing at alarming rates due to rampant deforestation across the archipelago (Gicaraya and Española, 2024; H. I. Mynott et al., 2021; Reintar et al., 2022). As forest habitats disappear or become fragmented, the specialised food sources these birds depend on become scarce or inaccessible, leading to a population decline (Brooks et al. 1999). By contrast, generalist feeders exhibit greater resilience because their flexible diets allow them to exploit alternative food sources in areas of degraded or secondary growth (Bregman et al. 2016; Atwood et al. 2020). This dietary flexibility buffers them against habitat disturbances, enabling them to persist in areas that specialists cannot (Keinath et al. 2017; Tanalgo et al. 2019). The case of Philippine birds mirrors global patterns where specialised trophic interactions increase extinction risk but are particularly acute in island ecosystems where species have evolved in isolation with narrow ecological niches (Duncan and Blackburn 2007; Boyer and Jetz 2014; Chichorro et al. 2022).

## **4.4. Major threats to Philippine terrestrial vertebrates**

Habitat alteration and overexploitation are the most pervasive threats to species, but their effects vary significantly across taxonomic groups. Amphibians, which rely on both aquatic and terrestrial habitats, are excessively affected by habitat destruction (87% of species), whereas their lower mobility and high microhabitat specificity make them less resilient than birds, which can often adapt or relocate (only 37% are impacted). The strong association of threats between families and endemism highlights the evolutionary uniqueness of these groups, meaning that habitat destruction could lead to irreversible biodiversity loss.

While the Philippines is a major country for endemism, it has one of the highest deforestation rates in Southeast Asia (Brooks et al. 1999; Global Forest Watch 2022; Gabriel 2023). Despite the establishment of over 240 protected terrestrial areas covering about 15% of its land (UNEP-WCMC and IUCN 2025), many face challenges due to insufficient management and threats from illegal activities such as logging and land conversion. Between 2001 and 2022, the country lost 1.42 million hectares of tree cover, representing a 7.6% decrease in total tree cover, which now stands at around 18.68 million hectares (Global Forest Watch 2024). This unprecedented forest loss would heavily affect habitat specialist species (Liu et al. 2024; Cervantes-López and Morante-Filho 2024).

Reptiles and mammals are significantly affected by overexploitation due to hunting, pet trade, and traditional medicine, in addition to facing similar challenges from habitat loss (Brandis et al. 2023). Endemic species with limited ranges and small populations are especially vulnerable, suggesting that exploitation often targets unique, range-restricted wildlife, valued for their rarity and distinctiveness (Scheffers et al. 2012; Hughes 2017, 2021). Subsistence hunting and illegal wildlife trade have intensified biodiversity loss, with sharp declines in many vertebrate populations documented since the 1980s (Harrison et al. 2016a). These pressures drive local extinction and disrupt ecosystems (Cruz 2021). In the Philippines, the archipelago's unique biogeography and high endemism exacerbate these effects, as many species fulfill critical ecological roles and are especially vulnerable to overexploitation (Hughes, 2017; Hughes, 2021; Scheffers et al., 2012; Tanalgo et al., 2023). This selective pressure, combined with weak law enforcement and socioeconomic challenges, amplifies the risks to native species and ecosystems (Shively 1997; Harrison et al. 2016b; Tanalgo 2017).

Invasive species and diseases largely threaten 7% of amphibians, most likely from diseases such as chytrid fungi and introduced predators (Diesmos et al. 2008; Swei et al. 2011). For example, the cane toad (*Rhinella marina*), introduced in the 1930s, now populates over 85% of the Philippine Islands (Pili et al. 2019). Moreover, competition for scarce resources allows them to outcompete native amphibians for critical resources such as food, breeding locations, and shelter. Since many amphibians in the Philippines are habitat specialists, often found only on specific islands or mountain ranges, the introduction of invasive species can swiftly disturb the fragile ecological balance. This situation is exacerbated by habitat loss and fragmentation (Diesmos et al. 2006; Rickart et al. 2011; Pili et al. 2019). Conversely, climate change threatens at least 12% of endemic birds in vulnerable island ecosystems, possibly affecting elevational migrants or species with narrow climatic niches (Şekercioğlu et al. 2012; Kittelberger et al. 2021). However, threats of climate change remain a minor but growing concern, especially for climate-sensitive species such as amphibians and reptiles (Diesmos et al. 2002; Bickford et al. 2010; Alcalá et al. 2012).

## **4.5. Who gets saved? Blind spots in Philippine biodiversity**

Our understanding of global biodiversity is far from uniform, with knowledge being unevenly distributed across the tree of life (Trimble and Van Aarde 2010; Buechley et al. 2019; Mammola et al. 2023). In our analysis, we found apparent differences and mismatches in research efforts, measured by the number of studies and GBIF occurrence records. Mammals and birds have received greater attention in terms of

the number of studies in contrast with amphibians and reptiles, which have been poorly studied. We consistently observed significant differences in both the number of studies and occurrence records in GBIF across conservation status categories, with the non-threatened groups receiving more research attention. This finding is consistent with Shuai et al. (2024) but contrasts with Caldwell et al. (2024), whose conclusions are based largely on specific subsets of conservation biology journals. Our observed variation and taxonomic bias for Philippine terrestrial vertebrates are consistent with prior analyses, which may be attributed to species traits and ecological status (Donaldson et al. 2017; Moura and Jetz 2021; Guedes et al. 2023).

Larger bodied species, broader habitat breadth, and year of description of research effort reflect a persistent bias toward larger, more widespread, and historically well-documented species (Moura and Jetz 2021; Guedes et al. 2023; Shuai et al. 2024). These traits likely increase detectability and discovery, making such species a more convenient research focus than smaller species (Collen et al. 2004; Diniz-Filho et al. 2005; Shuai et al. 2024). For example, common fruit bats, such as *Cynopterus brachyotis* and *Rousettus amplexicaudatus* (Tanalgo and Hughes 2018), which occupy broader habitats, have been studied more than Philippine carnivores (Fernandez et al. 2025). Although we observed congruence in species richness and occurrence patterns between amphibians and reptiles, the latter exhibited more variable and less predictable patterns, which is consistent with the findings of Abdullah et al. (2023). Amphibians are generally easier to detect due to their distinctive breeding behaviours and seasonal activity patterns. In wetter environments such as rainforests, they often become more visible, emerging from concealment and producing audible calls that aid identification (Aide et al. 2013; Dubos et al. 2020). In contrast, reptiles do not vocalise or produce distinctive sounds, making their detection and observation more challenging (Hoefler et al. 2023). Birds have been relatively well studied because of their conspicuousness and behaviours, such as distinctive coloration and vocalizations, which make them easier to observe and identify in the field (Teixeira et al. 2019; Hoefler et al. 2023). For example, even in high-conflict areas, birds remain reliable indicators of biodiversity because of their widespread presence (Hilario-Husain et al. 2024).

Additionally, while threatened species and endemism are often associated with larger-bodied species (i.e., more easily detectable), our findings indicate that threatened species remain understudied, as evidenced by the relatively low number of Google Scholar mentions. This lack of research attention is likely due to their restricted geographical ranges and lower population densities, which make them more difficult to locate and study (Amori and Gippoliti 2000; McKenzie and Robertson 2015). For instance, despite their high conservation priority, many narrowly endemic species with small population sizes may not receive the same level of scientific attention as more widespread or abundant species (Marshall et al. 2016; Shuai et al. 2024). Furthermore, we argue that conservation interests and research efforts are often directed toward charismatic megafauna, such as the Philippine Eagle (*Pithecophaga jefferyi*), Philippine Crocodile (*Crocodylus mindorensis*), and Tamaraw (*Bubalus mindorensis*), whereas other equally threatened but less iconic species have received far less attention. This bias in conservation focus, sometimes referred to as the “flagship species effect,” can lead to gaps in research and funding

for lesser-known taxa, even if they face similar or greater extinction risk (Marshall et al. 2016; McGowan et al. 2020; Berti et al. 2020).

In contrast to the significant predictors of the number of studies, smaller birds and mammals were recorded more frequently in the GBIF. This trend is particularly evident in the Philippines, where native terrestrial mammal communities are dominated by small-bodied species (e.g., rodents and bats) (Heaney et al. 2016). Large mammals are threatened and have become increasingly scarce because of habitat alterations and overhunting. Sampling approaches and how animals behave further amplify this disparity (Michelangeli et al. 2016; Hughes et al. 2021). In the Philippines, native terrestrial mammal communities are dominated by small-bodied species, such as rodents and bats (Heaney et al. 2016; Gamalo et al. 2021; Fernandez et al. 2025), whereas large mammals are increasingly scarce and threatened due to habitat alterations and overhunting, and sampling approaches and animal behaviour further amplifying this disparity (Michelangeli et al. 2016; Hughes et al. 2021). Studying large terrestrial vertebrates typically demands intensive field techniques, including the use of camera traps, radio telemetry, and systematic transect surveys, which are often conducted in remote and difficult-to-access areas. While these methods yield fewer records compared to more conventional techniques, the data they provide are often highly detailed and valuable for understanding species behaviour, distribution, and ecology (Harley and Eyre 2024; Bruce et al. 2025). Nevertheless, the considerable financial, logistical, and technical requirements of these approaches restrict their broader application in mammalian research in the Philippines (Gamalo et al. 2021; Fernandez et al. 2025). Whilst, small vertebrates (e.g., rodents, bats, and passerine birds) are easily captured in bulk via mist nets, pitfall traps, or acoustic monitoring, leading to disproportionately high specimen collection rates (Duan et al. 2024; Winiarska et al. 2024). Compared to larger-bodied species, smaller species are generally more abundant, adaptable to human-modified habitats, and easier to detect, potentially making them overrepresented in citizen-science-driven datasets of GBIF (Cardillo et al. 2005; Ripple et al. 2014; Troudet et al. 2017; Crees et al. 2019).

Consequently, the weak congruence between research effort and GBIF records suggests that, while some species are frequently studied, their occurrence data may remain sparse due to uneven sampling or data mobilisation efforts. Our analysis further shows how GBIF's data biases reflect not only species traits, but also regional ecological realities. The fact that non-endemic species have received more research attention (except in GBIF records, where endemics are better represented in some groups) further underscores how logistical and geographic constraints shape scientific inquiry.

## **4.6. Spatial shortfalls**

The underrepresentation of threatened species in both research and occurrence records has direct consequences for extinction risk assessments and conservation efforts (Quan et al. 2018; Daru et al. 2019; Chowdhury et al. 2023). Species with limited data are more likely to be classified as Data Deficient (DD) by the IUCN, potentially masking their true conservation status and delaying targeted intervention (Bland et al. 2015; Borgelt et al. 2022). This is particularly evident in mammals, where at least 37% of DD records are found in protected areas, suggesting that even when these species occur in managed

habitats, they remain critically understudied. The relatively lower PA coverage for threatened species occurrence further exacerbates their vulnerability because inadequate representation in protected areas leaves them more exposed to anthropogenic threats. The uneven distribution of research efforts across IUCN categories, especially for critically endangered reptiles and amphibians, highlights the mismatch between conservation needs and scientific attention (Shuai et al. 2024). Given that these groups face some of the highest extinction risks due to habitat loss, climate change, and disease (e.g., chytridiomycosis in amphibians), the lack of research undermines evidence-based recovery efforts (Watson et al. 2011; Kearney et al. 2020).

Addressing these biases requires targeted funding for understudied taxa, improved data mobilisation for threatened species, and stronger integration of occurrence records into conservation planning. Expanding protected area networks to better encompass threatened species, particularly reptiles and amphibians, could mitigate some risks but must be paired with enhanced monitoring and research. Additionally, leveraging citizen science and museum collections could help fill gaps in occurrence data for neglected species (Tingley et al., 2016).

Our findings highlight significant disparities in research effort and species observation across provinces, with clear shortfalls in some regions despite their potential biodiversity value. These disparities suggest that research and conservation activities are not aligned with ecological needs, potentially undermining national conservation outcomes.

Given these findings, conservation strategies and research initiatives must be recalibrated to operate more effectively at the provincial level. Provincial governments, local universities, and conservation organizations should be empowered and resourced to lead biodiversity monitoring and research within their jurisdictions (Agduma et al. 2023; Tanalgo et al. 2023a). Tailoring conservation efforts to regional contexts will help correct or improve existing biases and improve responsiveness to local ecological and sociopolitical conditions (Dela Cruz et al. 2023; Abdullah et al. 2023; Hilario-Husain et al. 2024). Future work should identify understudied provinces and invest in building local research capacity, including through community-based monitoring and partnerships with Indigenous and local knowledge holders (Bueser et al. 2003; Tumbaga et al. 2021; Panopio et al. 2021). Connecting these gaps is essential for a more equitable, comprehensive, and effective national conservation strategy.

## **5. Advancing conservation in the Philippines**

Our analysis represents the first extensive effort to investigate the drivers of extinction alongside biodiversity shortfalls in Philippine biodiversity, providing critical insights into patterns of species diversity, threat levels, and research attention across terrestrial vertebrate taxa. We found that species diversity varies widely, with amphibians exhibiting exceptionally high levels of endemism yet facing disproportionately elevated extinction risks. A large proportion of vertebrate species is threatened by widespread habitat destruction and overexploitation. Our findings underscore the urgent conservation priorities, particularly for amphibians and endemic lineages. High levels of endemism signify the

importance of preserving key habitats such as forest streams for amphibians and karst systems for reptiles, which offer disproportionately high conservation returns. However, significant knowledge gaps persist, particularly for reptiles, whose threat levels may be underestimated due to insufficient data.

Our findings emphasise the need for focused conservation efforts and sustained funding, particularly for taxonomic groups with unique evolutionary histories, which are both irreplaceable and highly threatened components of the Philippine biodiversity. Protecting intact and unique habitats, such as forests, forest streams, and karst systems, is essential for safeguarding species diversity, particularly for amphibians and reptiles that currently experience heightened extinction pressures. Additionally, reinforcing conservation policies and aligning national initiatives with global biodiversity frameworks would strengthen the protection of fragile ecosystems and wildlife populations.

Our study also revealed clear disparities in research efforts and data availability, reflecting the historical biases that continue to perpetuate conservation inequities. Without addressing these gaps, the most vulnerable and data-deficient species may remain overlooked until their decline is irreversible. Therefore, proactive, taxonomically balanced research investment is critical to ensure that conservation decisions are grounded in comprehensive, high-quality data, particularly for species on the brink of extinction.

Furthermore, mobilising occurrence data and improving data-sharing mechanisms will be vital for supporting evidence-based policies and conservation initiatives (Tanalgo 2025). Future efforts should prioritise expanded population monitoring, research into poorly known threats (e.g., disease, invasive species, impacts of changing climate), and the application of phylogenetic tools to identify evolutionarily distinct, at-risk species (Berba and Matias 2022). Policymakers should strengthen protected area networks, develop lineage- and family specific conservation strategies, and address persistent data deficiencies through citizen science initiatives, targeted field surveys, and genetic research.

Without urgent coordinated action informed by studies such as ours, the Philippines risks losing irreplaceable biodiversity, mainly its unique, highly endemic amphibians and reptiles. By identifying key conservation challenges, priority areas, and research gaps, our study offers an actionable roadmap to help ensure the survival of the country's remarkable and increasingly imperilled wildlife heritage.

## **Declarations**

## **Author Contribution**

KCT and KDC conceptualised the study. KCT led the manuscript writing. KCT, KDC, ARA, and AKL discussed and planned the analysis approach. KCT, KDC, ARA, and AKL supervised the project. JCE, RLD, JSA, BDV, and GPG organised and curated the data. KCT, KDC, ARA, and AKL reviewed the initial version of the manuscript. All authors reviewed the manuscript and approved the submission.

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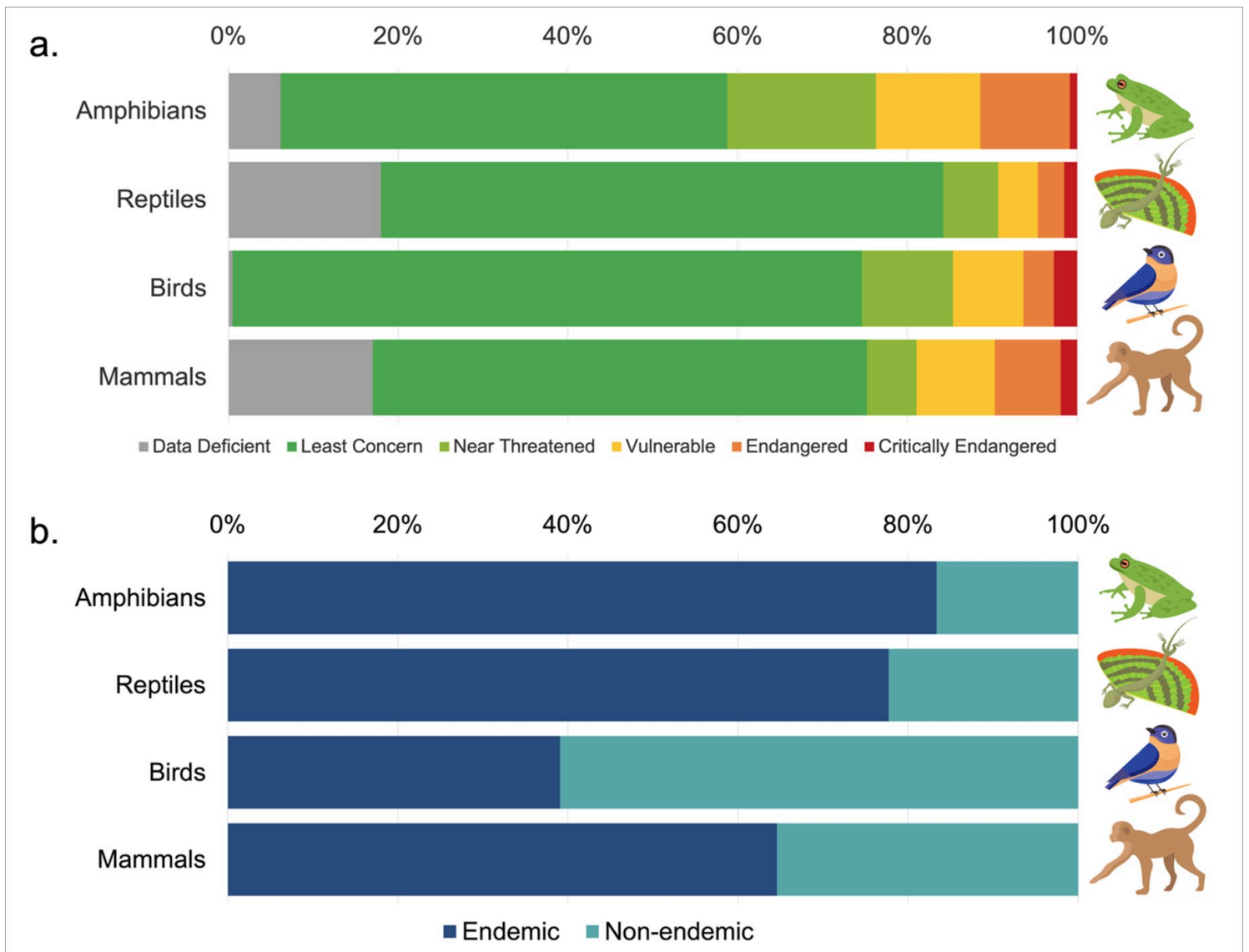
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## Supplementary Data

The Supplementary Data files S1-S4 are not available with this version.

## Figures



**Figure 1**

Distribution of Philippine terrestrial vertebrates according to their conservation status (a) and endemism (endemism) based on the IUCN Red List.

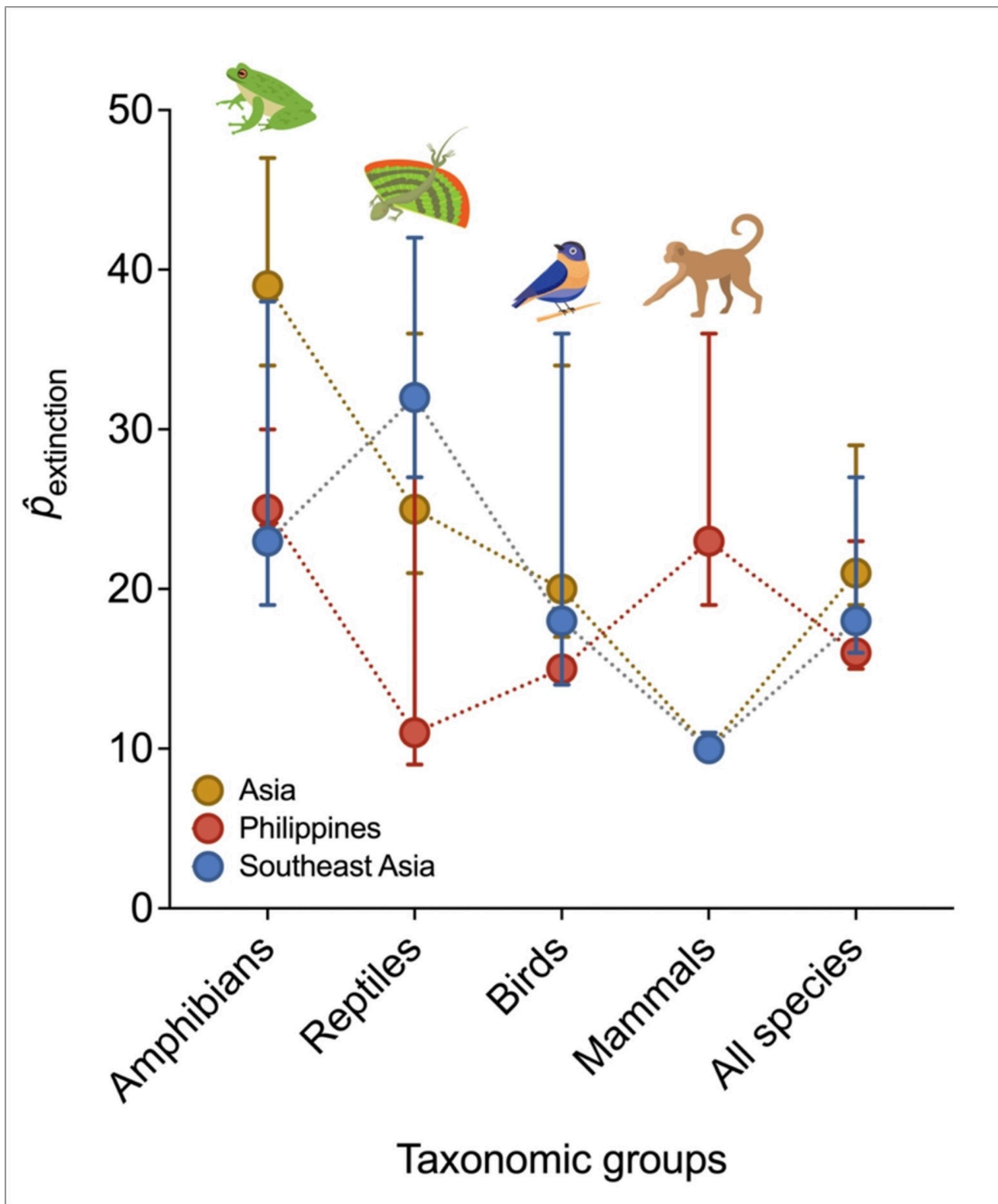
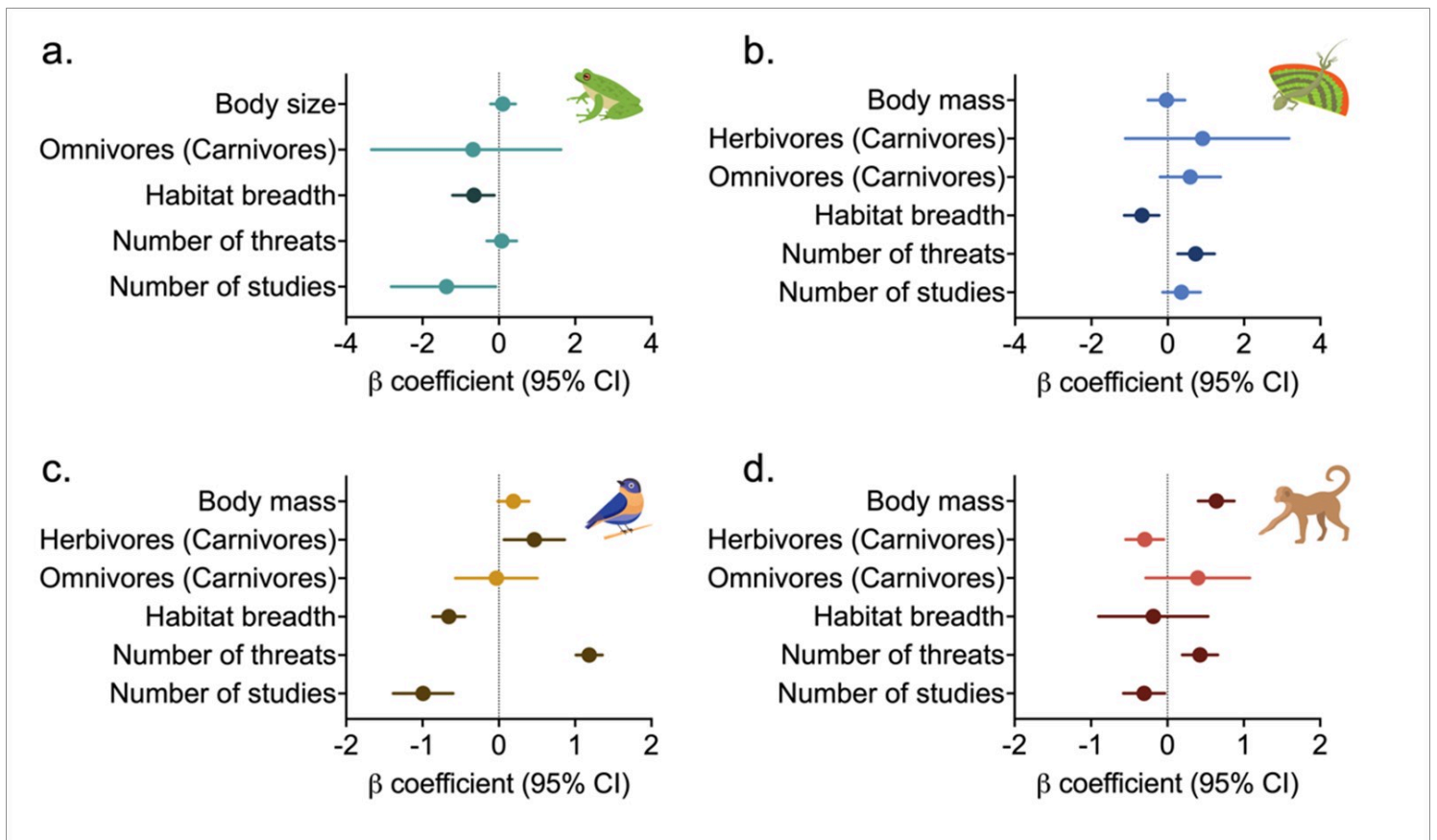


Figure 2

Extinction risk estimates for Philippine terrestrial vertebrates relative to Southeast Asia and continental Asia. Whiskers represent the lower upper estimates of the extinction risk estimates.



**Figure 3**

Visualised model results of extinction risk prediction across groups based on species life-history traits, number of threats, and number of studies. Dots and whiskers in bold indicate significance at  $p < 0.05$ .

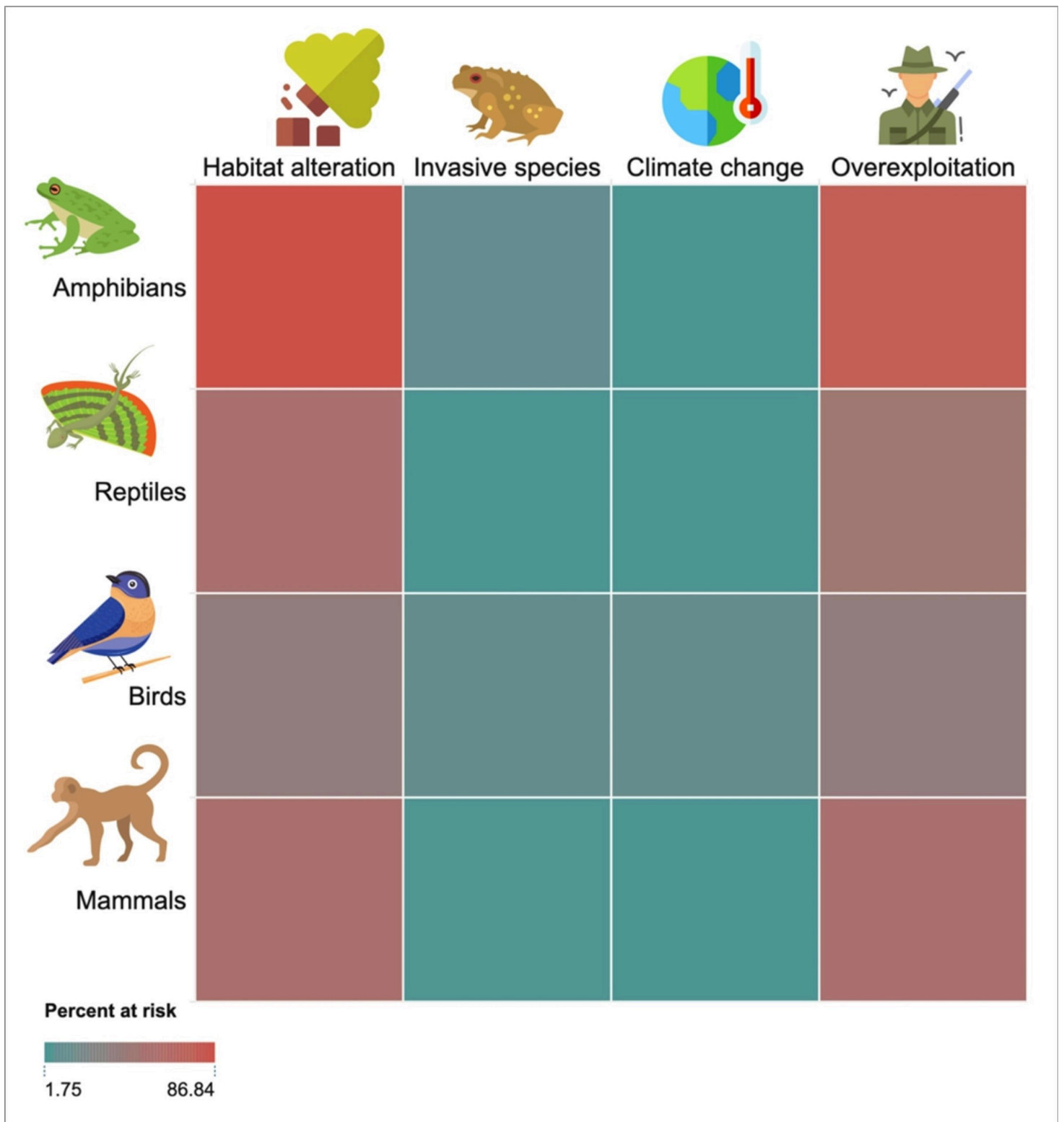
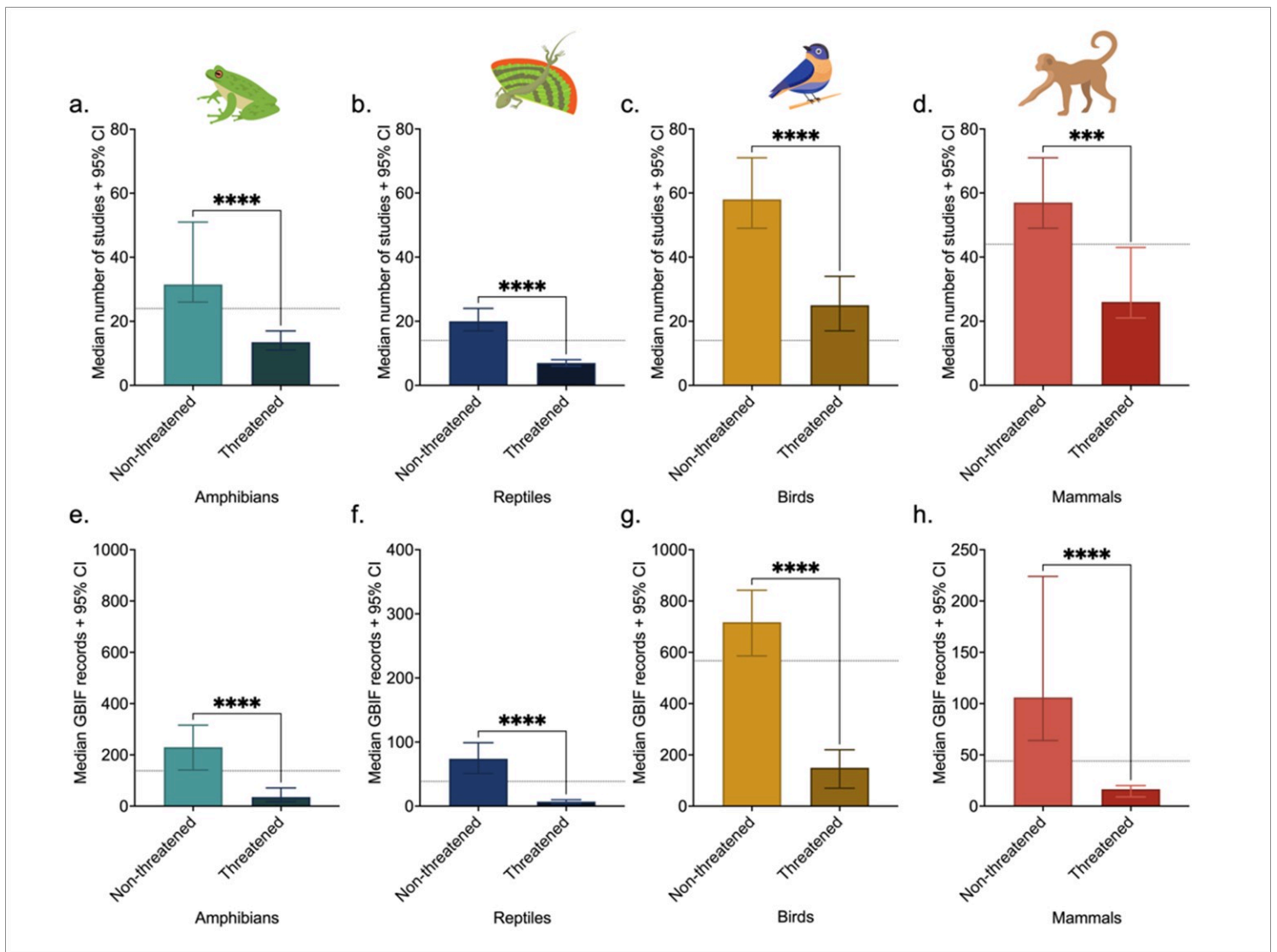


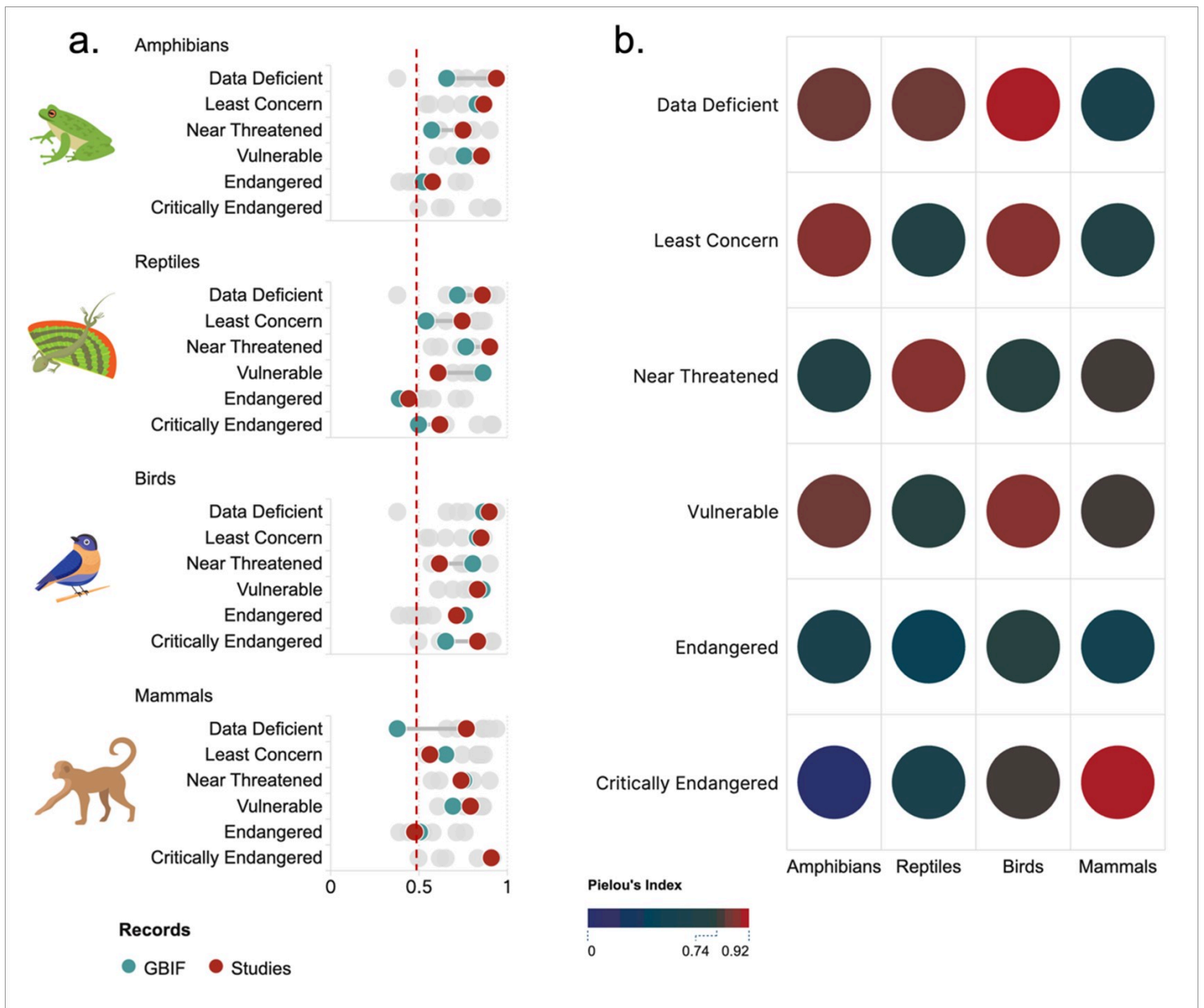
Figure 4

Percentage distribution of major threats across Philippine terrestrial vertebrates.



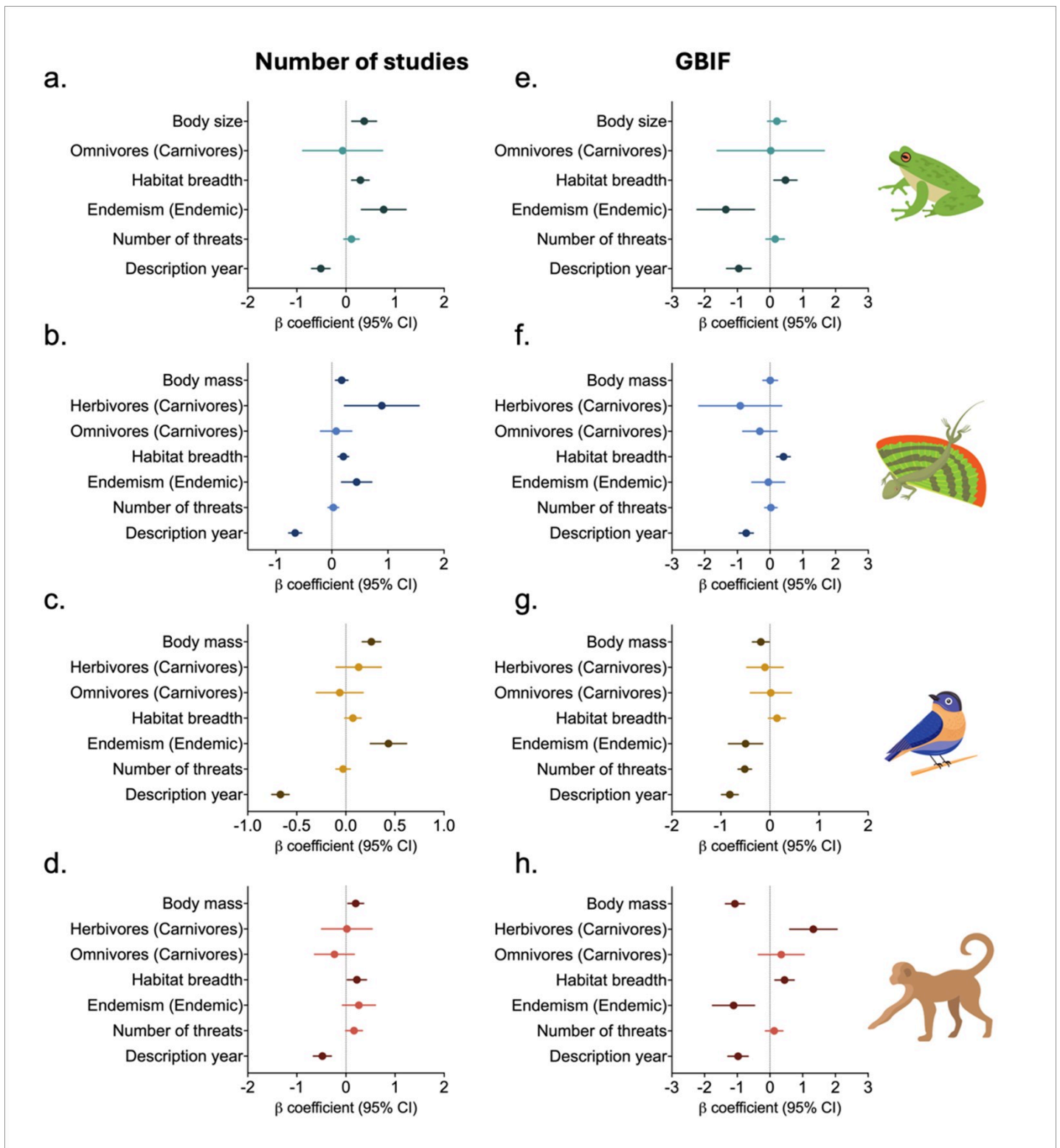
**Figure 5**

Comparison of research efforts based on Google Scholar hits (a-d) and GBIF occurrence records (e-h) across groups, compared between threat categories. The broken line represents the median value for the entire class and \*\*\*\* indicates significance at  $p < 0.0001$ .



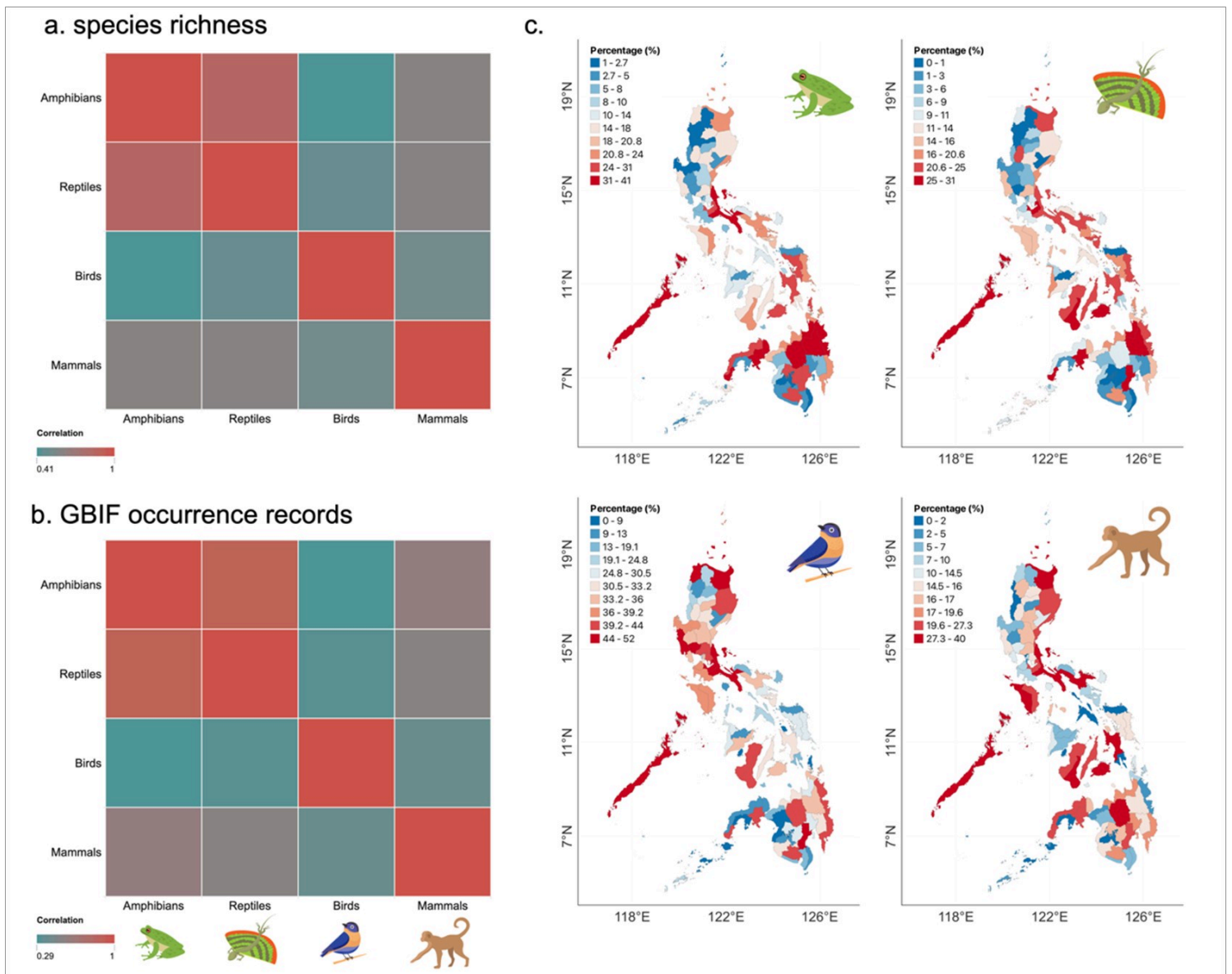
**Figure 6**

Variations in research effort bias indicated by Pielou's index, compared across conservation status (a) and congruences across groups.



**Figure 7**

Visualised model results predicting research efforts based on the number of Google Scholar hits (a-d) and GBIF occurrence records (e-h) compared across groups based on species life-history traits, number of threats, and number of studies. Dots and whiskers in bold indicate significance at  $p < 0.05$ .



**Figure 8**

Correlation matrix showing the spatial congruence in recorded species richness (a) and occurrence (b) records across groups, and patterns of normalised species richness (c), based on GBIF data. All correlation values were considered statistically significant at  $p < 0.05$ .

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [floatimage1.jpeg](#)