New species discoveries redefine global biodiversity patterns

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Abstract

Global biodiversity patterns are fundamental to ecology and conservation. However, these patterns are based on incomplete and rapidly growing taxonomic knowledge, and the influence of new species discoveries on our understanding of global biodiversity remains poorly understood. Here we quantified how the discovery of terrestrial vertebrates from 1920 to 2020 has reshaped estimated global diversity patterns and their inferred environmental drivers. New species discoveries were overwhelmingly concentrated in the tropics. For well-studied taxa such as birds, estimated diversity patterns remained largely stable, but reptiles and amphibians showed major reconfiguration: 20.3% and 31.7% of their respective diversity centers (top 5% of range-weighted rarity) shifted to new regions, including parts of Australia and Southeast Asia. These reconfigurations were accompanied by marked changes in inferred environmental drivers, with the apparent influence of temperature on richness declining and precipitation gaining importance. Our findings suggest that estimated global diversity patterns and driver relationships for poorly studied groups may be less reliable than often assumed. Consequently, projections of biodiversity change that rely mainly on temperature risk compromising conservation strategies. Our study calls for “more boots on the ground” to accelerate species discoveries and close critical biodiversity knowledge gaps.

Introduction

Understanding global biodiversity patterns and their environmental drivers is crucial in quantifying ecological and evolutionary processes, identifying conservation priorities, and informing strategies to mitigate biodiversity losses[1,2]. Global biodiversity has been extensively mapped for well-studied groups such as vertebrates[3–5] and plants[6,7], and increasingly for underrepresented taxa like invertebrates[8–10] and microorganisms[11]. However, these maps often suffer from inherent biases, stemming from uneven geographic coverage and incomplete taxonomic knowledge[12,13]. These limitations can bias biodiversity assessment, distort ecological and evolutionary inferences, and lead to suboptimal conservation decisions[14,15]. While geographic biases are increasingly recognized and addressed[16,17], the quantitative influences of incomplete taxonomic knowledge, which is a fundamental limitation known as the Linnean shortfall[18], on our understanding of global biodiversity remain largely unknown.

All taxonomic groups contain a substantial proportion of undiscovered species, with significant new discoveries in recent decades[19,20]. For example, while over 2,000 new vascular plant species are discovered annually[21], it is estimated as many as 100,000 species remain unknown[22]. This trend is also observed in well-studied taxonomic groups[23]. Between 1993 and 2008, 408 new mammal species were described, accounting for about 10% of previously known diversity[24,25]. Moreover, undiscovered and newly discovered species are disproportionately concentrated in biodiversity hotspots and remote areas[26,27]. Incomplete sampling in these often-inaccessible areas introduces substantial uncertainty into assessments of global biodiversity patterns, particularly for understudied taxonomic groups[28]. For example, the observed mid-latitudinal peak in global earthworm diversity likely reflects under-sampling in the tropics relative to well-sampled temperate regions[9], a discrepancy increasingly revealed by molecular studies uncovering the hidden earthworm diversity in the tropics[29]. Similarly, for ants, centers of richness and rarity are expected to shift significantly with greater sampling efforts[30]. Given that approximately 80% of Earth’s species are yet to be formally described[19], it is crucial to understand the distribution of species discoveries and their influences on estimated diversity patterns.

Species discoveries can also reshape ecological inferences regarding the relationships between diversity and environmental factors, challenging predictions about how biodiversity responds to global change. For example, the prevalence of new species discoveries in tropical regions may strengthen species-energy relationships by highlighting how more individuals of newly discovered species coexist[1]. Specifically, a hump-shaped relationship between diversity and mean annual temperature may be further evidenced due to the disproportionately high diversity in regions with high elevation and relatively cool temperature[27]. Conversely, the environmental heterogeneity hypothesis[31] may also gain further importance in explaining global biodiversity patterns as species discoveries continue to be made across tropical montane regions[25,32]. While recent studies have suggested climate as the dominant factor in explaining species richness patterns for different groups[7,33], the impact of new species discoveries on the relative role of different aspect of climate remains poorly understood. Addressing this major knowledge gap is critical for refining extinction risk assessment and informing conservation strategies, especially for data-deficient taxa[34].

Here, we used the IUCN Red List of Threatened Species[35], which includes up-to-date taxonomic and geographic information covering a broad range of taxa, to quantify how the inclusion of newly discovered terrestrial vertebrates alters patterns of species richness and rarity, and influences the environmental drivers that shape such patterns. We focused on terrestrial vertebrates because they are the primary targets of conservation efforts and represent a gradient of discovery completeness[5,24,36]. While we recognize that taxonomic changes (such as splitting and lumping) can increase or decrease species numbers independently of unknown species[37], our analysis quantified the influence of new discoveries by using species description dates to construct temporal discovery trends for vertebrates since 1920. This approach allowed us to disentangle the explicit influence of newly discovered species from the effects of heterogeneous sampling efforts across temporal and spatial resources. In this study, we addressed the following three key questions: 1) Where are newly discovered species concentrated? 2) To what extent do these discoveries redefine our understanding of global diversity patterns, such as the latitudinal diversity gradient[16] and diversity centers[2]? 3) How do new discoveries modify the inferred relationships between measures like species diversity and environmental drivers, which are essential for predicting the consequences of global change[10]?

Results

Geographic shifts in diversity patterns

We found that species discovered between 1920 and 2020 cumulatively constituted 39.6% (13,491 of 34,036 species) of total terrestrial vertebrate species, representing 7.7% (832 of 10,856) of birds, 31.7% (1,774 of 5,586) of mammals, 50.7% (5,012 of 9,880) of reptiles, and 76.1% (5,873 of 7,714) of amphibians (Table 1). Notably, 17.3% of reptiles and 33.0% of amphibians have been discovered since 2000 (Table 1). New species discoveries were strongly concentrated in the tropics, decreasing sharply towards the poles (Fig. 1). Therefore, species discoveries of vertebrates, especially for reptiles and amphibians, accentuated the unimodality of latitudinal diversity gradients (Fig. 1).

Across our 95-km-resolution grid, the number of species discoveries showed a significant relationship with species number in 1920 across all vertebrate groups ($p < 0.001$ for all four groups based on our generalized additive models; Fig. 2). Birds and amphibians showed a monotonically increasing number of new discoveries, whereas discoveries of new mammal species have declined in the most species-rich regions since 1920. Discoveries of reptiles peaked at a moderate level of historical richness and then plateaued. In particular, mammal discoveries were exceptionally low in the forests and savannas of Lake Victoria Basin in East Africa (a mammal biodiversity center), while we found disproportionately high number of discoveries in Papuan montane forests (Fig. 2c), implying shifting centers of mammalian species discovery over the past century. Australian savannas and shrublands exhibited an unexpectedly high number of new reptile species (Fig. 2e), increasing Australia's known diversity by 2.5-fold (from 376 species in 1920 to 933 species in 2020; Supplementary Fig. 1).

To assess shifts in diversity centers with high biogeographic uniqueness, we identified regions with the top 5% range-weighted rarity (emphasizing range-restricted species) and classified their dynamics into three categories: emergent diversity centers (newly identified after increasing taxonomic knowledge), historical diversity centers (initially identified but no longer significant following species discoveries), and stable diversity centers (persistent across all discovery scenarios). Newly discovered bird species had negligible effects on overall diversity patterns (Fig. 2b). However, we observed significant shift in diversity centers for mammals, with 12.1% of their total area replaced by emergent centers, a result of shrinkage in the Equatorial Afrotropics and expansion in the Central Andes, Madagascar, and Indonesian islands (Fig. 2d; Supplementary Table 1). The spatial change in diversity centers was even more pronounced for reptiles and amphibians, with 20.3% and 31.7% of their respective center areas being replaced (Supplementary Table 1). For reptiles, emergent centers predominantly appeared in the northern and western Australian savannas and shrublands (Fig. 2f). For amphibians, key emergent centers included the Andean montane forests and Southeast Asian tropical forests (Fig. 2h). These trends for mammals, reptiles and amphibians remain striking across different time periods and diversity metrics, with substantial shifts observed when considering only the past 20 years (4.3% for mammals, 5.0% for reptiles, 13.6% for amphibians) or species richness centers (11,2% for mammals, 17.4% for reptiles, 27.3% for amphibians; Supplementary Fig. 2-3 & Table 1).

Discoveries alter inferred drivers

Our analysis revealed contrasting temporal trends in the relationships between species richness and environment among vertebrate groups and environmental variables from 1920 to 2020 (Fig. 3; Supplementary Table 2). While the relationships for birds and mammals remained consistent, those for reptile and amphibian species exhibited substantial temporal changes (Fig. 3). Specifically, the dominant association with mean annual temperature weakened significantly for reptiles ($z = 2.01$, $p = 0.04$) and amphibians ($z = 3.70$, $p < 0.001$), as determined by a modified z-test of variable effect size between 1920 and 2020. Similarly, the influence of annual precipitation on reptile diversity showed a non-significant, yet clear, decline ($z = 1.58$, $p = 0.11$). In contrast, the contribution of precipitation-related factors generally increased for amphibian diversity, with a significant rise in the influences of precipitation seasonality ($z = 3.45$, $p = 0.001$). The association with elevation range, as a proxy for environmental heterogeneity, strengthened for reptiles ($z = -3.77$, $p < 0.001$) and amphibians ($z = -7.80$, $p < 0.001$). While the influence of temperature and precipitation anomalies since the Last Glacial Maximum remained largely consistent, precipitation anomalies showed a significant decline for reptile diversity pattern ($z = -2.10$, $p = 0.04$; Fig. 3, Supplementary Table 2).

As diversity-environment relationships can vary among biogeographic realms due to their divergent histories[38], we also analyzed these relationships at the realm level. The Ethiopian, Nearctic, and Palaearctic realms exhibited consistent environment-richness associations across all vertebrate groups (Fig. 4). However, for reptiles and amphibians in the Australian, Neotropical, and Oriental realms, the trends in relationships between species richness and temperature and precipitation were generally consistent with global patterns (Fig. 4, Supplementary Table 3).

Discussion

Geographic shifts in diversity patterns

The ongoing discovery of new species has profound implications for our understanding of global biodiversity, especially given the taxonomic and spatial biases inherent in these discoveries[13,18,39]. Our findings demonstrate that new species discoveries can substantially redefine global diversity patterns, particularly for understudied taxa (e.g., reptiles and amphibians) and less-explored regions (e.g., the tropical mountains). We show that species discoveries, which are heavily concentrated in the tropics, have steepened the latitudinal diversity gradient (Fig. 1). Indeed, the tropics not only host a high diversity of life[40], but are also home to the majority of the world's new and undiscovered species[41], such as vertebrates[25,27], ants[30], and plants[26]. However, counter to the expectation that high known diversity would correlate with a high number of species discoveries[26], our analysis revealed an opposite trend in some important areas (e.g., mammals in the Equatorial Afrotropics), resulting in a decline in their relatively importance as diversity centers. Instead, we identified several regions as emergent diversity centers, characterized by a disproportionately high number of newly discovered species (Fig. 2). This finding, which highlights newly identified diversity centers in the North Australian Savanna and West Australian Shrubland (for reptiles) and in the Amazonian and Southeast Asian

Forests (for amphibians), aligns with the concept of "hidden hotspots"[42] (underrecognized biodiverse regions due to incomplete knowledge) and "shifted hotspots"[43] (where the relative importance of regions as diversity hotspots changes once better biodiversity knowledge alter the global ranking) and extends their existence to a broader spatial and taxonomic scales. The identification of emergent centers not only redefines global biodiversity patterns, but also highlights previously underrecognized regions that now require emergent conservation attention.

Our study also revealed the critical role of historical sampling effort in shaping the temporal change of diversity patterns. We found that biodiversity patterns for well-studied groups (e.g., birds) and well-sampled regions (e.g., Palaearctic biogeographic realm) remained consistent despite ongoing species discoveries. This observation is likely a direct consequence of high historical sampling efforts in these areas [8,44], which have yielded a limited number of newly discovered species in recent years. Consequently, existing diversity patterns for these groups and regions are largely consistent [45]. In contrast, the temporal shift in amphibian diversity patterns in the Brazilian rainforest and Andean cloud forest is largely due to these regions having been historically under-sampled [46]. This finding highlights the importance of continued exploration and taxonomic efforts in under-sampled regions and taxonomic groups.

Discoveries alter inferred drivers

New species discoveries challenge our understanding of the environmental drivers of biodiversity patterns. We found a significant decline in the importance of mean annual temperature for explaining the number of ectothermic reptile and amphibian species, likely because new discoveries are skewed toward habitats with relatively cool temperatures. For example, the Strabomantidae family, which constitute an exceptionally high proportion of newly described amphibian species (Supplementary Fig. 4 & 5), is often found in cool and humid habitats, such as the historically underexplored Andean cloud and montane forests[46]. The discovery of numerous lizard species in deciduous forests also challenges the assumption that members of this group prefer hot and arid habitats[36]. As ectothermic vertebrates are generally sensitive to temperature[47], the discovery of many new species adapted to cool temperatures is critical. Overlooking these species together with weakened inferences of diversity-energy relationships, could risk neglecting the threats from rising temperatures, leading to underestimates future biodiversity loss. Moreover, precipitation-related factors have become increasingly important in inferring amphibian diversity, as most new amphibian species occur in tropical regions with relatively high rainfall[42,48]. Given increasing climate extreme events and induced dryness[47,48], the influences of precipitation and its variability may have more severe consequences on amphibians than previously thought. Conversely, the strength of inferred association between annual precipitation and reptile diversity has declined over time, driven mainly by discoveries of arid-tolerant lineages (e.g., lizards) in savanna regions of Australia and the Cerrado[36,43]. The increasing importance of environmental heterogeneity in shaping reptile and amphibian diversity further supports the need for ongoing field surveys in mountain and valley areas[27], particularly in the Neotropical and Oriental realms. Therefore, our results challenge the robustness of current biodiversity models and projections (e.g., species distribution models) that rely heavily on climate-richness relationships.

Implications

Our findings have important implications for global biodiversity conservation. Specifically, we found that a high proportion of diversity centers for mammals, reptiles, and amphibians have been replaced over the past century by newly identified centers in previously overlooked regions, yet these new centers are often threatened by deforestation and associated biodiversity loss[49]. As a result, we may also be underestimating hidden biodiversity loss in these regions[23]. In addition, since our study focused on vertebrates, which are relatively well-studied, global diversity patterns and ecological inferences derived from incomplete taxonomic knowledge may be even less reliable for poorly studied taxa. Indeed, studies on global patterns of earthworms and fungi, which are less-studied groups, have been criticized for their incomplete taxonomical surveys[9,15]. Therefore, it becomes more critical to incorporate unknown species into macroecological studies to effectively assess and guide conservation across different taxonomic groups[34], highlighting the need to improve biodiversity monitoring and close knowledge gaps, as emphasized by the Kunming-Montreal Global Biodiversity Framework. To effectively integrate new species discoveries into conservation management, we advocate developing new methods to predict the taxonomic and spatial distributions of undiscovered species (e.g., ref. 27), especially in tropical and montane areas.

While mean annual temperature has long been widely used in predicting future biodiversity changes under global warming[47], the shifting importance of temperature and precipitation we observed implies that temperature alone is insufficient to accurately predict species losses of ectothermic vertebrates. While obtaining reliable precipitation data and using it appropriately for future biodiversity predictions remains a significant challenge[48], integrating water availability constraints into assessments of climate change is a necessary step for designing effective protected areas.

We are aware that the observed temporal changes in global biodiversity patterns may not exclusively reflect new species discoveries but are also influenced by taxonomic change, such as species lumping and splitting[37]. Species additions from taxonomic change can constitute a significant proportion of newly described species (e.g., ref. 43, 45), and is expected to increase with advances in molecular technologies[24]. Our analyses, which focused on the temporal differentiation of known species numbers, are therefore not able to distinguish between new discoveries and species additions resulting from taxonomic change. Further interpretation of our results must be conducted with caution. Given that taxonomic change remains a significant challenge in biogeographical and macroecological research[37], future efforts should focus on integrating historical records of taxonomic change at broad taxonomic and spatial scales. This would allow for a more robust assessment of the influences of incomplete biodiversity knowledge, extending beyond the incomplete taxonomy to include other challenges such as a lack of species distribution knowledge.

Conclusion

Our work provides a dynamic perspective on estimated global biodiversity patterns, showing that ongoing species discoveries substantially alter our understanding of macroecological patterns and relationships. We found evidence of notable reconfigurations in the relative geography of diversity centers, as well as shifts in the inferred importance of environmental drivers, particularly for understudied groups such as reptiles and amphibians in the tropics. These findings indicate that current estimates of global diversity patterns and their drivers for poorly studied taxonomic groups are less reliable than often assumed, and that relying on them may compromise conservation planning under climate change. Addressing these challenges requires renewed taxonomic and survey efforts, especially in tropical and montane regions. We therefore echo Wilson's[50] call for “more boots on the ground” to accelerate species discoveries and close critical biodiversity knowledge gaps.

Materials and Methods

Data compilation

We compiled species range maps from multiple sources for terrestrial vertebrates. For birds, we used data from the Handbook of the Birds of the World and BirdLife International version 7[51]. For mammals and amphibians, we used the International Union for Conservation of Nature Red List of Threatened Species[35]. We sourced reptile species range maps from Roll et al.[5]. We filtered the range polygons for all taxa to include only extant, native or reintroduced species. Following the guideline of the IUCN mapping standards, we included species with a presence code of 1-3 (extant, probably extant, possibly extant), an origin code from 1-2 (native, reintroduced), and a seasonal code from 1-3 (resident, breeding, non-breeding). For reptiles, we included all available range maps, as they all represent extant and native species. Our dataset comprised range maps for 10,856 bird, 5,586 mammal, 9,880 reptile, and 7,714 amphibian species.

Taxonomy

We standardized species nomenclature and taxonomic authorities for all taxa to ensure consistency. For birds, we followed the taxonomy of the Handbook of the Birds of the World and BirdLife International version 7[51]. For mammals and amphibians, we used the IUCN Red List[35], supplemented with The Mammal Diversity Database[24] and Amphibian Species of the World 6.2[52] where IUCN data were incomplete. For reptiles, we first referenced The Reptile Database[53] checklist (version 2 March 2024). We then resolved any discrepancies by cross-referencing against The Reptile Database synonym checklist (version April 2023) and synonyms listed in the IUCN Red List[35]. We conducted additional literature searches to complete taxonomic authority information for reptile species when necessary.

Diversity patterns

To analyze global diversity patterns, we first aggregated species range maps onto a global hexagonal grid. We used the ‘dggrid’ R package[54] to create grid cells, with each cell covering an area of 7,774 km^2. The hexagonal grid can minimize geographic distortions in area and distance, making it suitable for macroecological studies[55]. We then overlaid the grid with global land cover data, excluding any cells that the remaining land area was less than half of the original cell size. Within each remaining cell, we determined the presence and number of species by intersecting with species ranges.

To explore temporal dynamics of global vertebrate diversity gradients under species discoveries, we estimated diversity patterns at 10-year intervals beginning in 1920, representing a time span of one century. We did this by considering the cumulative number of species described and published up to the end of each time period. The latest description date in our dataset was 2019 for birds, 2020 for mammals and amphibians, and 2015 for reptiles. For convenience, we hereafter refer to 2020 as the upper time limit for all groups.

To account for the potential effects of biogeographic history[38], we assigned each hexagonal grid cell to one of six zoogeographic regions: Australian, Neotropical, Nearctic, Palearctic, Ethiopian, and Oriental. This delineation followed the work of Holt et al.[56] and Ficetola et al.[57]. In total, our final analyses included 9,716 bird, 5,245 mammal, 8,646 reptile, and 7,267 amphibian species.

Environmental variables

To identify the environmental relationships for vertebrate diversity, we selected environmental variables that reflect contemporary climate, environmental heterogeneity, and past climate change. These variables have been used widely as important predictors of vertebrate diversity[58–61]. We sourced present climatic conditions from the Climatologies at high resolution for the earth's land surface areas (CHELSA) dataset at a resolution of 30 arc-sec[62]. We included mean annual temperature (bio1), annual range of temperature (bio7), annual precipitation (bio12), precipitation seasonality (bio15), and mean monthly precipitation of the warmest quarter (bio18). We initially considered other variables representing climate harshness, such as temperature seasonality (bio4), mean daily minimum air temperature of the coldest month (bio6), and mean monthly precipitation amount of the driest quarter (bio17), but excluded them due to high collinearity with other selected climatic variables (Pearson's $r > 0.7$). Environmental heterogeneity was represented by elevation range, calculated as the difference between maximum and minimum altitude from the Global multi-resolution terrain elevation data 2010 at a resolution of 30 arc-sec[63]. The magnitude of past climate change was quantified using temperature and precipitation anomalies from Last Glacial Maximum (~21,000 years ago), measured as the difference between present and LGM conditions derived from CHELSA-TraCE21k[64].

Analyses

Estimation of diversity metrics

We evaluated vertebrate diversity patterns using two diversity metrics: species richness and range-weighted rarity[65]. We calculated species richness as the total number of species present in each hexagonal grid cell. To emphasize the conversation value of narrow-ranging species, we also calculated range-weighted rarity. We derived this metric by summing the rarity value of each species within a given cell, where rarity of a species was defined as the inverse of the number of cells it occupied. This approach is frequently used to prioritize conservation efforts for species with restricted ranges[10,30,36]. Considering the inherent L-shaped distribution of species ranges in our dataset, where a majority of species are narrowly distributed, we adjusted the rarity calculation to prevent disproportionate influence of highly restricted species. We therefore added a constant offset to the denominator, that is the number of occupied cells, in the rarity calculation. This constant value was set as the 75th percentile of the overall species ranges for each vertebrate group. This method can balance the influences of narrowly distributed species, avoiding the creation of too many high-rarity "islands" while still emphasizing their conservation importance.

Identifying diversity centers

To evaluate the temporal dynamics of biodiversity centers over the past century, we identified the top 5% and 10% of hexagonal grid cells for both species richness and range-weighted rarity. These cells, which represent the highest diversity, were considered as diversity centers. These centers were identified for time periods 1920 and 2020 in our analysis. We then tracked the spatial shifts in these centers by comparing their locations across different time periods.

Spatial models

To explore the shifts in the relationships between species diversity and environmental variables over time, we performed linear regressions of species richness against environmental variables. These explanatory variables included contemporary climate (mean annual temperature, temperature range, annual precipitation, precipitation seasonality, and precipitation of the warmest quarter), environmental heterogeneity (elevation range), and past climate change (anomaly in temperature and precipitation since Last Glacial Maximum). We natural log-transformed species richness, and square root-transformed environmental variables to reduce the skewness. We then standardized all variables to zero mean and unit standard deviation for comparison across models.

Given the detection of significant spatial autocorrelation in our initial linear models, we used simultaneous autoregressive regressions (SAR) with the error type, implemented with the 'spatialreg' R package[66]. To define the spatial neighbor structure for the SAR models, we used a distance band approach. We determined the optimal distance by iteratively testing a distance from 100 km to 3000 km in an increment of 200 km. We selected the best distance that yielded the lowest Akaike information criterion (AIC), highest Nagelkerke's pseudo R^2, and an insignificant Moran's I test for residual spatial autocorrelation. With the appropriate distance, spatial autocorrelation was significantly accounted for. As biogeographic history might vary among regions[38], we repeated the spatial model analysis independently for each biogeographic realm.

To test for the difference in the effect of environmental factors on species richness between 1920 and 2020, we utilized a z-test. As species richness of these two time periods are from the same locations and violate the assumption of independence, we incorporated the covariance between the coefficient estimates in our z-test. To correctly estimate the coefficient covariance, we first extracted the residuals from each spatial model. These residuals were then transformed using the spatial error parameter and a weight matrix. This allowed us to compute the coefficient covariance. The z-test was formulated as follows:

$$z = \frac{\beta_1 - \beta_2}{\sqrt{SE(\beta_1)^2 + SE(\beta_2)^2 - 2 \times Cov(\beta_1, \beta_2)}}$$

Here, β_1 and β_2 are the coefficients of the environmental factor from two spatial models, $SE(\beta)$ represent the standard error for each coefficient, $Cov(\beta_1, \beta_2)$ represent the estimated covariance between the two coefficients. A P value less than 0.05 from the z-test indicates a significant difference between the two coefficients across the two time periods.

Data availability

Species range maps are availability from several public repositories: birds from the Handbook of the Birds of the World and BirdLife International version 7 (https://datazone.birdlife.org); mammals and amphibians from the IUCN Red List of Threatened Species (https://www.iucnredlist.org/); and reptiles from ref. 5 (https://doi.org/10.1038/s41559-017-0332-2). Taxonomic data are available as follows: birds from the Handbook of the Birds of the World and BirdLife International version 7 (https://datazone.birdlife.org); mammals from the IUCN Red List of Threatened Species (https://www.iucnredlist.org/) and The Mammal Diversity Database (https://www.mammaldiversity.org/); reptiles from The Reptile Database (https://reptile-database.org/); amphibians from the IUCN Red List of Threatened Species (https://www.iucnredlist.org/) and Amphibian Species of the World 6.2 (https://amphibiansoftheworld.amnh.org/). Environment data are available at CHELSA (https://chelsa-climate.org/) and GMTED2010 (http://pubs.er.usgs.gov/publication/ofr20111073).

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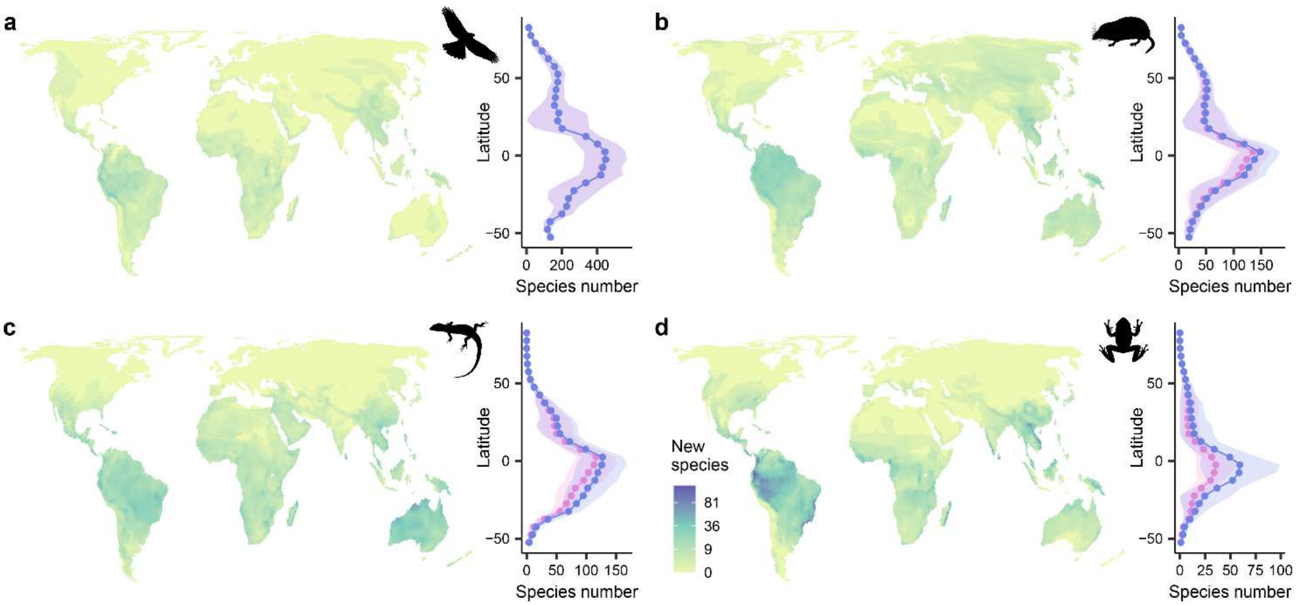

Fig. 1 New species discoveries in the tropics steepen the latitudinal diversity gradient. a-d, Maps show the diversity of new species discovered between 1920-2020 for birds (**a**), mammals (**b**), reptiles (**c**), and amphibians (**d**). The plots illustrate the corresponding shift in the latitudinal diversity gradient (LDG) for total species number in 1920 (red) and 2020 (blue). All maps use an identical color scale. In the plots, solid circles represent mean species number per 5-degree latitudinal band, and the shaded area indicates the standard deviation (s.d.) around the mean. Silhouettes are from PhyloPic (credits: a, Andy Wilson; b, Leonardo Ancillotto; c, Kailah Thorn; d, Vijay Karthick).

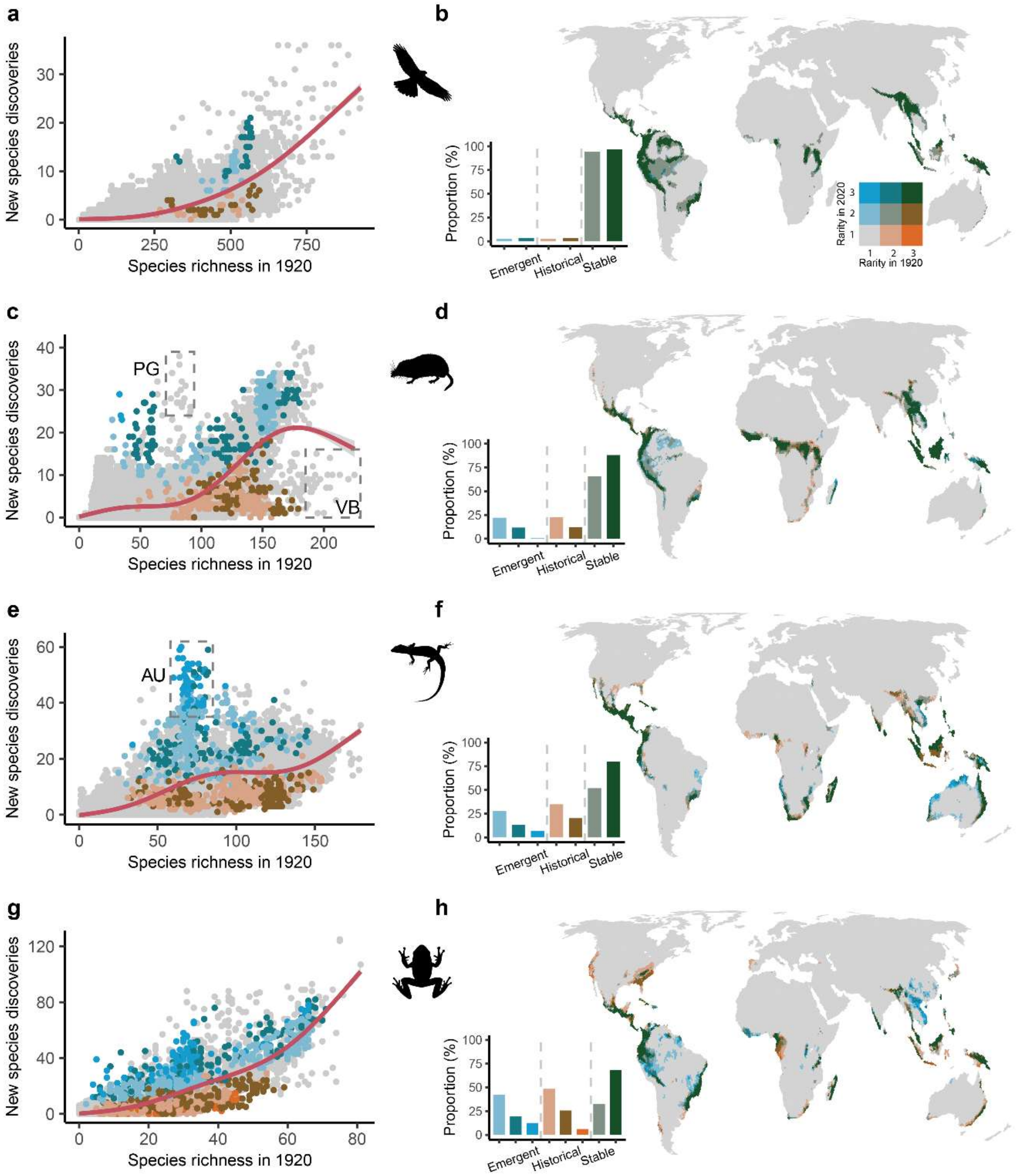

Fig. 2 New species discoveries reshaped estimated diversity patterns. a, c, e, g, The relationship between species richness in 1920 and subsequent discoveries (1920-2020) for birds, mammals, reptiles, and amphibians. The solid lines represent a generalized additive model spline. Annotated labels highlight regions: Papua New Guinea (PG); Victorica Basin (VB); Australia (AU). **b, d, f, h,** Maps show the shift in diversity centers of range-weighted rarity between 1920 and 2020. Dark shades indicate regions in the top 5% of rarity, medium shades the top 5-10%, and light shades and grey indicate regions outside the top 10%. Shifted diversity centers are highlighted in color: emergent centers (regions that emerged as diversity centers after new species discoveries, blue), historical centers (regions initially identified as diversity centers but have since diminished, brown), and stable centers (regions that remained stable across discoveries, green). Inset bar plots show the proportion of shifted diversity centers for each group. Silhouettes are from PhyloPic (credits: a, b, Andy Wilson; c, d, Leonardo Ancillotto; e, f, Kailah Thorn; g, h, Vijay Karthick).

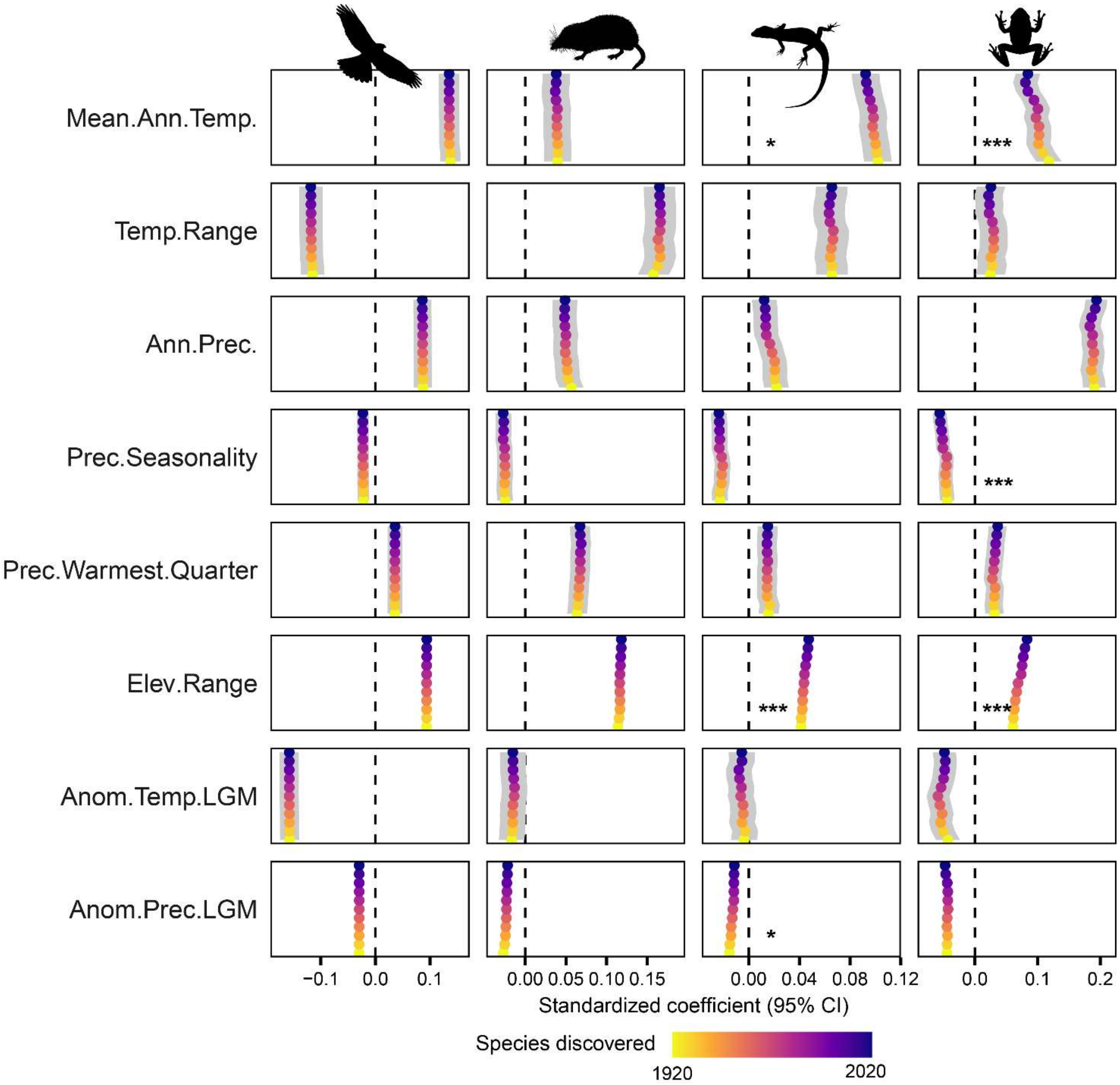

Fig. 3 Shifts in estimated relationships between environment and vertebrate diversity at the global scale. Standardized coefficients from simultaneous autoregressive models illustrate the change in species richness relationships for birds, mammals, reptiles, and amphibians from 1920 to 2020. The shaded grey area represents the 95% confidence interval. Significance was tested using a modified z-test to control for the temporal dependence. Asterisks indicate a significant difference in environmental variable coefficients between 1920 and 2020: $P < 0.001$ (***), and $0.01 < P < 0.05$ (*). Mean.Ann.Temp., mean annual temperature (bio1); Temp.Range, annual range of temperature (bio7); Ann.Prec., annual precipitation (bio12); Prec.Seasonality, precipitation seasonality (bio15); Prec.Warmest.Quarter, mean monthly precipitation of the warmest quarter (bio18); Elev.Range, elevation range; Anom.Temp.LGM, temperature anomaly since Last Glacial Maximum; Anom.Prec.LGM, precipitation anomaly since Last Glacial Maximum. Silhouettes are from PhyloPic (credits: Andy Wilson, bird; Leonardo Ancillotto, mammal; Kailah Thorn, reptile; Vijay Karthick, amphibian).

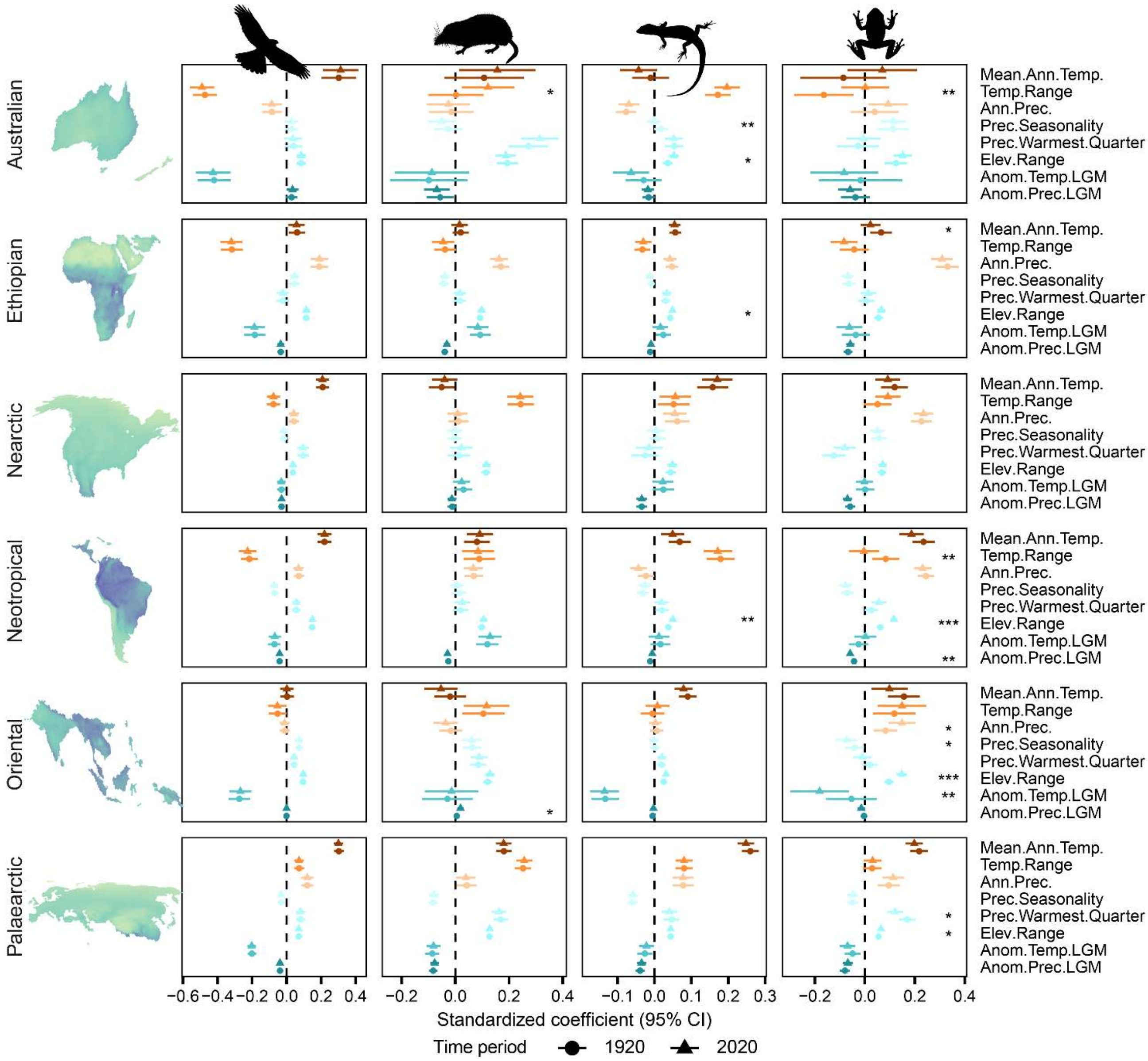

Fig. 4 Contrasting environmental driver estimates for vertebrate diversity across biogeographic realms. Standardized coefficients from simultaneous autoregressive models represent predictors of species richness in 1920 (circles) and 2020 (triangles). Panels show results for birds (left), mammals (middle left), reptiles (middle right), and amphibians (right). Error bar indicates 95% confidence intervals. Biogeographic realm map is shown in gradient of known vertebrate diversity in 2020. Significance was tested using a modified z-test to control for the dependence between 1920 and 2020. Asterisks indicate a significant difference in environmental variable coefficients between 1920 and 2020: P < 0.001 (***), 0.001< P < 0.01 (**), and 0.01< P < 0.05 (*). Mean.Ann.Temp., mean annual temperature (bio1); Temp.Range, annual range of temperature (bio7); Ann.Prec., annual precipitation (bio12); Prec.Seasonality, precipitation seasonality (bio15); Prec.Warmest.Quarter, mean monthly precipitation of the warmest quarter (bio18); Elev.Range, elevation range; Anom.Temp.LGM, temperature anomaly since Last Glacial Maximum; Anom.Prec.LGM, precipitation anomaly since Last Glacial Maximum. Silhouettes are from PhyloPic (credits: Andy Wilson, bird; Leonardo Ancillotto, mammal; Kailah Thorn, reptile; Vijay Karthick,amphibian).

Table 1 Number and proportion of discovered terrestrial vertebrate species between 1920 and 2020. Proportion of discovered species within each time period is shown in parentheses.

Time period	Birds	Mammals	Reptiles	Amphibians
1920-1940	408 (3.8%)	466 (8.3%)	755 (7.6%)	629 (8.2%)
1940-1960	134 (1.2%)	204 (3.7%)	525 (5.3%)	500 (6.5%)
1960-1980	87 (0.8%)	241 (4.3%)	845 (8.6%)	941 (12.2%)
1980-2000	111 (1%)	357 (6.4%)	1,179 (11.9%)	1,256 (16.3%)
2000-2020	92 (0.8%)	506 (9.1%)	1,708 (17.3%)	2,547 (33%)
1920-2020	**832 (7.7%)**	**1,774 (31.7%)**	**5,012 (50.7%)**	**5,873 (76.1%)**