

Climate change is projected to shrink phylogenetic endemism of Neotropical frogs

Received: 22 May 2024

Accepted: 4 April 2025

Published online: 19 April 2025



Gabriela Alves-Ferreira ^{1,2}✉, Neander M. Heming ¹, Daniela Talora¹, Timothy H. Keitt ², Mirco Solé ^{1,3} & Kelly R. Zamudio ²

Climate change is widely recognized as one of the main threats to biodiversity¹ and predicting its consequences is critical to conservation efforts. A wide range of studies have evaluated the effects of future climate using taxon-based metrics^{3,4}, but few studies to date have applied a phylogenetic approach to forecast these impacts. Here, we show that future climate change is expected to significantly modify not only species richness, but also phylogenetic diversity and phylogenetic endemism of Neotropical frogs. Our results show that by 2050, the ranges of 42.20% ($n = 213$) of species are projected to shrink and the range of 1.71% of species ($n = 9$) are projected to disappear. Furthermore, we find that areas of high SR and PD are not always congruent with areas of high PE. Our study highlights the projected impacts of climate change on Neotropical frog diversity and identifies target areas for conservation efforts that consider not just species numbers, but also distinct evolutionary histories.

Climate change is one of the main threats to biodiversity^{1,2}. Over the past century, human activities have led to rises in the emission of greenhouse gasses, resulting in an increase of Earth's surface temperature¹. As a consequence, there has been renewed interest in understanding effects of climate change by forecasting the persistence of species in future environments³. These forecasting attempts have focused on many different species traits and roles. For example, studies have evaluated the effects of climate change on geographic ranges, biotic interactions, population dynamics, and ecosystem functions^{4–8}. However, biodiversity is not just about species, but also about the information contained in the topology and branches of phylogenetic trees, which carry important information about the evolutionary history of species⁹. Given the magnitude of projected climate change, it is a priority to conserve the evolutionary heritage of biodiversity¹⁰. The conservation of species with distinct genetic heritage may be key for adaptation to future non-analogous climatic conditions caused by global warming¹⁰.

Prior studies have concentrated on documenting and forecasting changes in diversity based on species richness (SR)^{3,4}. However, this approach undervalues the important contribution of evolutionary history and thus may miss key aspects of diversity related to

innovations arising in the diversification of clades. Phylogenetic diversity (PD) is a widely used metric that assesses the shared evolutionary history of species by using the sum of the branch lengths of all species that inhabit a given region¹¹. These branch lengths represent the amount of evolutionary change that occurred since lineages diverged from a common ancestor, reflecting both the time and the evolutionary processes that led to species' current adaptations. Regions with high PD may consist of areas containing many species from a species-rich clade, or alternatively, a few species with long branches. Conversely, if a region has many species but several are closely related, the PD score will be lower¹¹.

PD does not take into account rarity in species' distributions¹². A second metric, developed to address this shortcoming, is phylogenetic endemism (PE), which integrates evolutionary heritage with information on species distributions^{12,13}. PE identifies areas with potential loss of evolutionary history through the sum of the branch lengths of a set of species that occur in a given region, weighted by species range sizes^{12,13}. Thus, PE measures the spatial restriction of the evolutionary history of species, which can depend on the total distribution of the set of species that occur in a region, the range size of each species, and the amount of evolutionary history shared among them¹².

¹Programa de Pós-graduação em Ecologia e Conservação da Biodiversidade, Universidade Estadual de Santa Cruz, Ilhéus, BA, Brazil. ²Department of Integrative Biology, College of Natural Sciences, The University of Texas, Austin, TX, USA. ³Zoologisches Forschungsmuseum Alexander Koenig, Herpetology Section, Bonn, North Rhine-Westphalia, Germany. ✉e-mail: gabriela-alves77@hotmail.com

PD is expected to decrease with climate change, while PE should increase and be spatially displaced to new areas that are predicted to remain climatically suitable¹⁰. The increase in PE is a consequence of species becoming more restricted spatially in the future¹⁰. Therefore, as species distribution decreases, endemism patterns are expected to increase, increasing PE values. While some species are expected to experience range contractions, others may benefit from the new climatic conditions and expand their distributions, possibly decreasing endemism patterns and PE values. One way to forecast the effect of projected future climate change on the tree of life is through the combination of species distribution models (SDMs¹⁴) and diversity metrics¹⁵. SDMs associate occurrence data with environmental variables to predict the potential distribution of species in time and space¹⁴. Combining SDMs and metrics of evolutionary heritage can identify areas that need to be conserved now to increase the retention of those unique aspects of the tree of life. Including evolutionary proxies can provide a way to identify regions with a rich and spatially restricted evolutionary legacy that need to be prioritized for conservation¹⁶.

Amphibians are the most threatened vertebrate class (40.3% of species are endangered¹⁷), and they are highly impacted by climate change, as most species depend on very specific climatic conditions and have limited dispersal capacity¹⁸. Currently, approximately 3000 species of amphibians are known from the Neotropics, and 94% of those are endemic to the region¹⁹. The Neotropics face other severe anthropogenic pressures including deforestation and over-exploitation of natural resources, which combined with climate change, are rapidly leading to high rates of species loss and potentially phylogenetic losses as well. Here, we ask how future scenarios of climate change will affect patterns of SR, PD, and PE of Neotropical frogs (toads -Bufonidae and treefrogs -Hylidae). Projected increases in temperature and reductions in precipitation are expected to shrink the potential distributions of species, resulting in lower SR and PD in the future. We also expect that regions predicted to lose SR will be congruent with the regions predicted to lose PD in the future, given the spatial correlation between the two metrics. In contrast, we expect PE to increase, due to reductions in potential distributions. However, the exact degree to which PE increases will depend on the relative reduction in species' distributions and the identity of species that are lost.

We show that by 2050, the ranges of 42% of species are expected to shrink and 1.71% to disappear. Decreasing range areas in response to climate change could lead to a meltdown in ecosystems, and potential loss of functional and genetic diversity in the future. Our models also reveal projected shifts in geographic patterns of SR, PD, and PE in the future and show that some centers of high PE are not areas of particularly high SR or high PD. Identifying regions predicted to have high PE in the future have particular importance from a conservation perspective, as these areas are likely to harbor species with distinct genetic heritage crucial for adaptation to non-analogous climatic conditions.

Results

General patterns of loss and gain of range areas

The model metrics obtained through block cross-validation showed a good fit, with mean values of Area Under Curve of 0.78 and Omission Rate of 0.08 (Supplementary Table 2). Our projections indicate that 42.20% ($n = 213$) of species are expected to suffer a reduction in range by 2050 under the pessimistic climate scenario. Furthermore, 1.71% ($n = 9$) of frog species are projected to completely lose their ranges by 2050 (Table 1), including *Aplastodiscus leucopygius*, *Boana microderma*, *Boana platanera*, *Boana ventrimaculata*, *Dendropsophus bokermanni*, *Dendropsophus stingi*, *Exerodonta xera*, *Hylascirtus armatus*, and *Rhinella ornata* (Table 1). Some of these species have long branch lengths, such as *Dendropsophus stingi* (16.579 Myr) and *Boana*

microderma (14.337 Myr) (Table 1). In contrast, many species ($n = 304$, 57.79%) are projected to gain range areas, among them *Megastomahyla mixe*, *Incilius spiculatus*, *Megastomahyla nubicola*, *Dryophytes cinereus*, and *Charadrahyla altipotens* (Supplementary Data 2).

Most of the species that are projected to lose range areas in the future are classified as Least Concern (LC) by the IUCN (Fig. 1a and Supplementary Table 2). We also identified seven species (four toads and three treefrogs) currently categorized as threatened (Vulnerable -VU, Endangered -EN, or Critically Endangered -CR) projected to lose range area (Fig. 1a and Supplementary Table 2). Our models indicate that while fewer species (213) are expected to lose their range in the future, these species belong to lineages sharing a similar average amount of evolutionary history when compared to those projected to expand their range (304 species) (Fig. 1b). Furthermore, the mean projected decrease in range area (mean = $-8.366 \pm 11 \text{ km}^2$ and $\text{SD} = 1.430 \pm 11 \text{ km}^2$) is significantly larger than the mean projected increase (mean = $7.109 \pm 11 \text{ km}^2$ and $\text{SD} = 1.424 \pm 11 \text{ km}^2$) in range area ($W = 1401$, $p\text{-value} < 0.001$, Fig. 1c). The estimated direction of change in future range size is influenced by current range sizes, and species with large current ranges are projected to have a higher decrease in their ranges in the future than species with small current ranges (Spearman's rank correlation = -0.571 , $p < 0.001$; Supplementary Fig. 3).

The most important variables in predicting range areas for toads were the Precipitation of Driest Quarter (BIO 17), Annual Precipitation (BIO 12), and Annual Mean Temperature (BIO 1) (Supplementary Table 3). For treefrogs, the most important variables were the Annual Mean Temperature (BIO 1), Mean Temperature of Warmest Quarter (BIO 10), and Minimum Temperature of Coldest Month (BIO 6) (Supplementary Table 3).

Species richness patterns

Our models reveal that Neotropical frogs are predicted to have two large regions with high SR; the first in southeastern Brazil, and the second in northwestern South America, including northwest Brazil, eastern Ecuador, northeastern Peru, and southern Colombia (Fig. 2a and Supplementary Fig. 4a). However, according to our forecasts, SR is expected to change in several regions, in both optimistic and pessimistic emission scenarios (Fig. 2b and Supplementary Fig. 4b). The regions projected to have the highest reduction in SR, under both optimistic and pessimistic scenarios, are the Guiana Shield, eastern Venezuela, eastern and northeastern Peru, southeast, northwest, northern and central Brazil, and northeastern and southeastern Bolivia (Fig. 2c and Supplementary Fig. 4c). The models also predict regions where the SR will increase in the future, including southern Mexico, Costa Rica, central Ecuador, central Colombia, southern Peru, and Central Bolivia (Fig. 2c and Supplementary Fig. 4c).

Phylogenetic diversity patterns

As expected, regions that harbor high PD in the present are the same areas predicted to harbor high SR (Fig. 2d and Supplementary Fig. 4d). Likewise, PD projected in the future is spatially congruent with areas forecast to have high SR in 2050 (Fig. 2e and Supplementary Fig. 4e). Our models project a marked decrease in PD in the Guiana Shield, northern Mexico, central and northern Argentina, Cuba, central and northern Brazil, eastern Amazon, and the northern Andes (Fig. 2f and Supplementary Fig. 4f). The models also predict an increase in PD in the future in the same regions predicted to have an increase in SR (Fig. 2f and Supplementary Fig. 4f).

PD is predicted to be higher than SR in the present across northern Colombia, Venezuela, western Peru, western Chile, central Brazil, southern Bolivia, Uruguay, and northern Paraguay (positive values of SES PD, Fig. 2g and Supplementary Fig. 4g). Conversely, SR is

Table 1 | Species projected to lose all of their range area by 2050 with the percentage of loss under both pessimistic and optimistic emission scenarios, their threat category according to the IUCN (2024), and branch length (Myr)

Species	Family	Country	IUCN category	Branch length	% loss- Optimistic	% loss- Pessimistic
<i>Aplastodiscus leucopygius</i>	Hylidae	Brazil	LC	5.302	−99.944	−100
<i>Boana microderma</i>	Hylidae	Colombia, Peru, and Brazil	LC	14.337	−100	−100
<i>Boana platanera</i>	Hylidae	Panama, Colombia, Venezuela, and Trinidad and Tobago	LC	3.572	−99.955	−100
<i>Boana ventrimaculata</i>	Hylidae	Ecuador and Brazil	LC	0.371	−99.862	−100
<i>Dendropsophus bokermanni</i>	Hylidae	Colombia, Ecuador, Peru, and Brazil	LC	3.342	−99.895	−100
<i>Dendropsophus stingi</i>	Hylidae	Colombia	LC	16.579	−54.775	−100
<i>Exerodonta xera</i>	Hylidae	Mexico	VU	3.031	−100	−100
<i>Hyloscirtus armatus</i>	Hylidae	Peru and Bolivia	NT	8.494	−89.318	−100
<i>Rhinella ornata</i>	Bufo	Brazil and Argentina	LC	0.795	−99.416	−100

LC Least Concern, NT Near Threatened, VU Vulnerable.

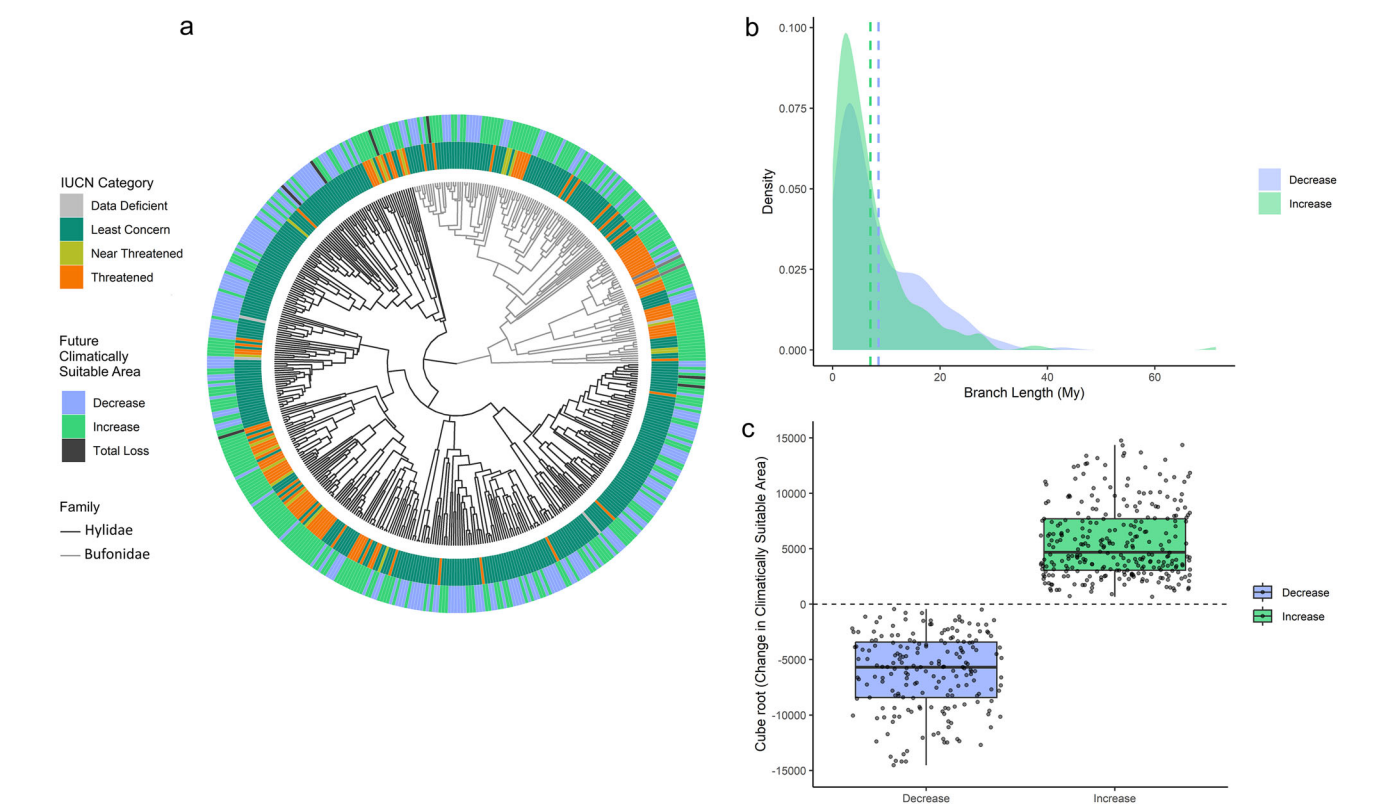


Fig. 1 | Phylogenetic tree of 497 Neotropical frogs in the families Hylidae (treefrogs) (black branches) and Bufonidae (toads) (gray branches) and the values of branch length and change in climatic suitable area for species. a shows the phylogenetic tree for the studied frogs, the future range area, and IUCN category. In the legend, the orange color represents threatened species, which includes Critically Endangered, Endangered, and Vulnerable, the yellow color represents Near Threatened species, green color represents Least Concern species, and gray color represents Data Deficient species. Light green colors represent species projected to increase range area in the future, purple color represent species projected to lose a part of their area, and black color represent species

projected to lose their entire range area in the future. **b** presents the density of branch length for species projected to lose and gain range area in 2050. The dotted lines in **(b)** represent the means of branch lengths for species expected to increase and decrease range area. The **(c)** displays a boxplot of the projected change in climatically suitable area for species. In the boxplot, the horizontal black line represents the median, the box indicate the interquartile range, and the whiskers extend to the minimum and maximum values. Black dots represent the individual change in range area for each species. The dataset consists of frog species, with $n = 213$ species in the Decrease category and $n = 304$ in the Increase category. Source data are provided as a Source Data file.

expected to be higher than PD in the present (negative values of SES PD, Fig. 2g and Supplementary Fig. 4g) in Mexico, Jamaica, Cuba, northern Peru, as well as in southeastern, northern, and central Brazil. In the future, SR is predicted to be higher than PD in Cuba, Jamaica, western Chile, western Peru, southern Mexico, and northern Brazil (Fig. 2h, i and Supplementary Fig. 4h, i).

Phylogenetic endemism patterns

We also predicted current centers of PE and projected their change into the future. PE is currently concentrated in the Guiana Shield, southeastern Brazil, the northern Andes, southern Mexico, nuclear and Isthmian Central America (Guatemala, Honduras, and Costa Rica), Jamaica and northern Cuba (Fig. 3a and Supplementary Fig. 5a).

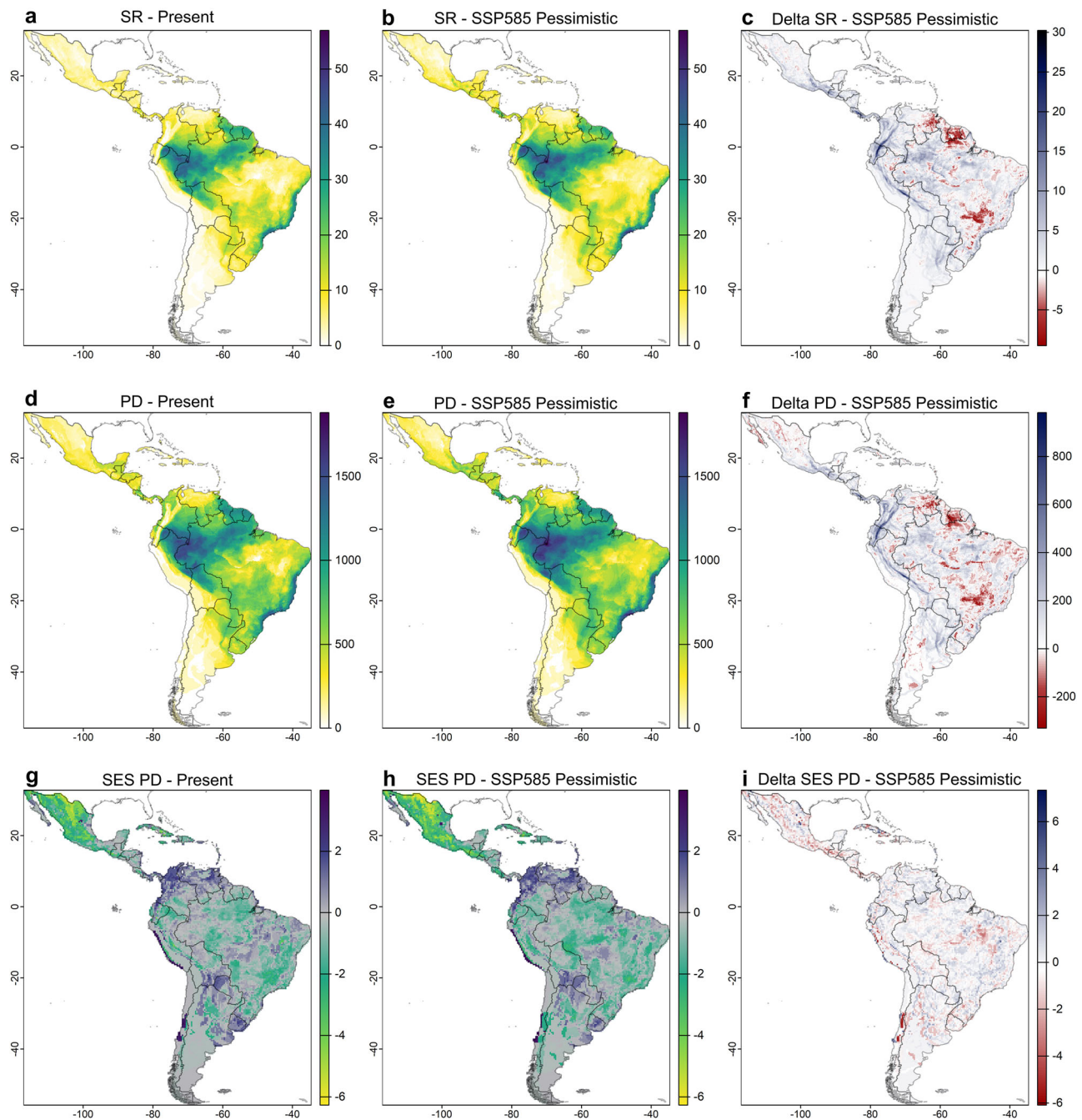


Fig. 2 | Species richness (SR), Phylogenetic diversity (PD), and Standardized effect size for Phylogenetic diversity (SES PD) of 497 Neotropical toads and treefrogs. a SR for the present scenario. **b** SR for the pessimistic 2050 scenario. **c** Differences in SR between present and the pessimistic 2050 scenario. **d** PD for the present scenario. **e** PD for the pessimistic 2050 scenario. **f** Differences in PD between present and the pessimistic 2050 scenario. **g** SES PD for the present. **h** SES PD for the pessimistic 2050 scenario. **i** Differences in SES PD between present and the pessimistic 2050 scenario. Purple and dark green colors represent regions

predicted to have high SR and PD, while light green and yellow colors represent regions predicted to have low SR and PD. Red colors represent species losses in SR, PD, and SES PD, gray/white color represents areas where SR, PD, and SES PD are not predicted to change, and blue color represents SR, PD, and SES PD gains in the future. In the (g, h) yellow and green colors represent regions where PD is lower than expected randomly and blue and purple colors represent regions where PD is higher than expected randomly.

Climate change is projected to shift the spatial patterns of PE across the Neotropics, in both optimistic and pessimistic emission scenarios (Fig. 3b, c and Supplementary Fig. 5b, c), resulting in centers of PE more spatially restricted. The value of PE in most regions is expected to decrease substantially in the future, mainly for Guiana Shield, southern Mexico, Panama, Ecuador, and southeastern Brazil (Fig. 3b, c and Supplementary Fig. 5b, c). The exceptions projected to increase PE in the future are northwestern and southeastern Colombia, southeastern

Costa Rica, and a small center in southern Brazil (Fig. 3b, c and Supplementary Fig. 5b, c).

Relationship between diversity metrics

As predicted, PD and SR showed a very strong relationship in the present (Pseudo $R^2 = 0.993$) and in the future (Pseudo $R^2 = 0.994$, Supplementary Fig. 6a–c), but the magnitude of the relationship varies across space. SR and PD are both high in Guiana Shield, southeastern

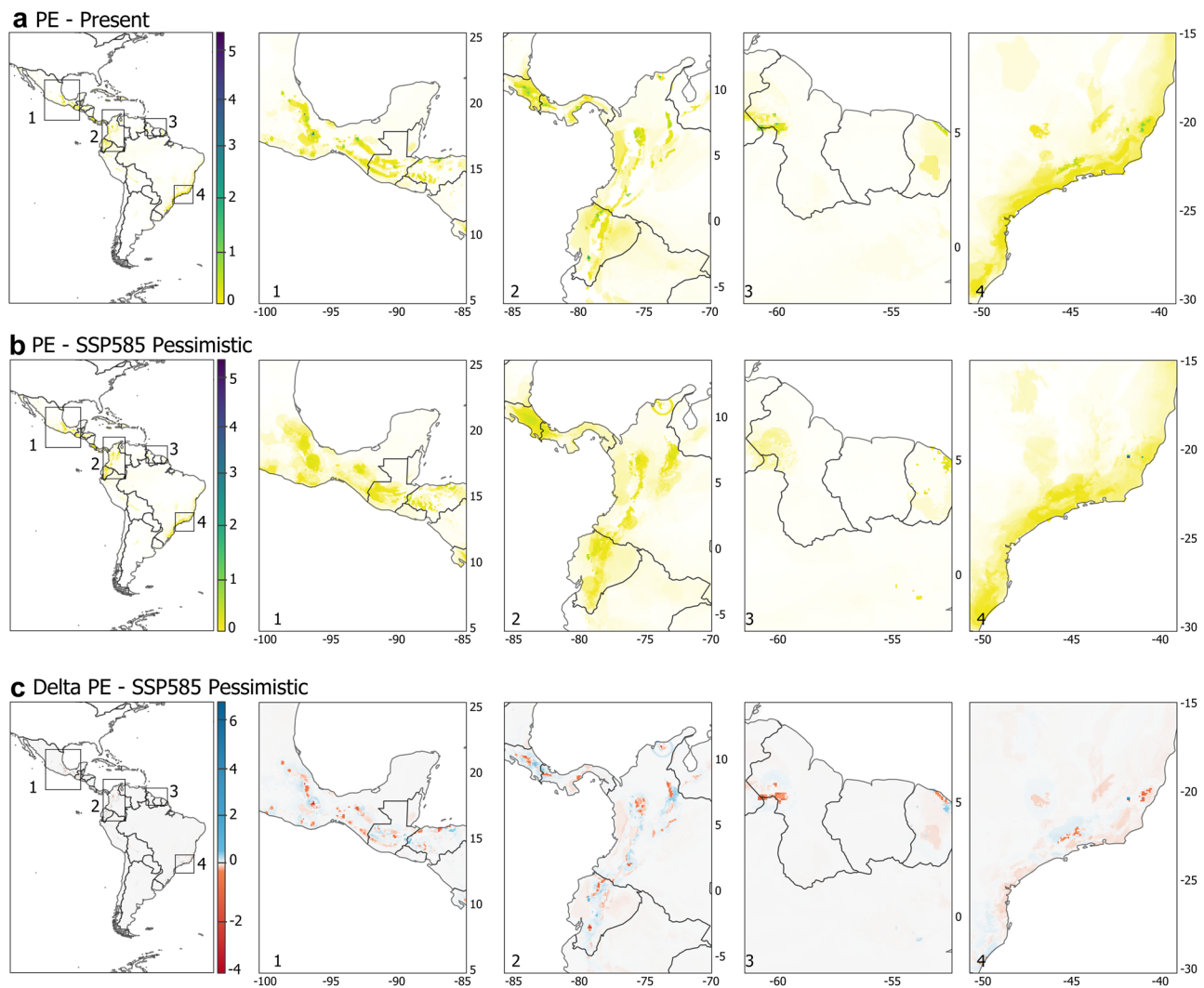


Fig. 3 | Phylogenetic endemism (PE) of 497 Neotropical toads and treefrogs. **a** PE for the present scenario. **b** PE for the pessimistic 2050 scenario. **c** Differences in PE between present and the pessimistic 2050 scenario. In **(a, b)** purple and green colors represent regions predicted to have high PE, while yellow colors represent

regions with low PE. In **(c)**, red colors represent losses in PE, gray/white color represents areas where PE is not predicted to change, and blue color represents PE gains in the future.

and northern Brazil, eastern Peru, Colombia, Ecuador, and Bolivia (Fig. 4a–c). PE showed a weak relationship with SR in the present (Pseudo $R^2 = 0.017$) and future (Pseudo $R^2 = 0.047$, Supplementary Fig. 6d–f). Regions where both PE and SR are high are located in southeastern Brazil, Amazon (Brazil, Peru, Ecuador, and Colombia), Costa Rica, and French Guiana (Fig. 4d–f). PE is higher than SR in southern and northern Mexico, nuclear and Isthmian Central America (except by Costa Rica), Caribbean Islands (Cuba, Haiti, Jamaica, Dominican Republic, and The Bahamas), southern Brazil, western Colombia, Ecuador, and Central Chile (Fig. 4d–f). Our models suggest important areas for the conservation of the phylogenetic component (higher PD and SES PD, Fig. 4g–i) in southeastern and northern Brazil, southern Paraguay, northern Bolivia, northeastern Peru, eastern Colombia, southern Venezuela, and northern Guyana (Fig. 4g–i).

Discussion

Our models indicate that almost half (42.20%) of the studied frog species are expected to experience a reduction in their range areas, with nine species (1.71%) predicted to lose their entire range by 2050. The future climate change is also predicted to shift the SR, PD, and PE of Neotropical frogs and make communities more clustered spatially. However, the loss of PD and, mainly, PE in some regions can be much

more severe than the loss of SR. The reduction in PD and PE can be driven by the loss of species with long branch lengths, which represent deep evolutionary histories. These branch lengths reflect the amount of evolutionary divergence accumulated over time, and the loss of such species can lead to a significant reduction in the unique evolutionary history of Neotropical frogs.

Some species projected to lose range are threatened according to the IUCN red list (VU, EN, CR)²⁰, which underscores an urgent need for targeted conservation action. To be categorized as threatened, a species must be suffering substantial extinction risk due to threats such as disease (chytridiomycosis for anurans), habitat loss, fragmentation, or invasive species²⁰. Adding climate change to this mix of stressors²¹ will make the persistence of the species in changing habitats much more challenging. Some examples of threatened toad species are the Harlequin frogs (genus *Atelopus*), which have been suffering reductions in their populations due to pathogen spread (chytridiomycosis), habitat loss, and the indirect interaction of climate change with disease agents²². These species should be a priority for global conservation and their populations must be monitored to avoid potential declines or extinctions in the next 30 years. Moreover, species classified as “Least Concern” (LC) that are projected to lose range area underscores that the conservation status of non-threatened

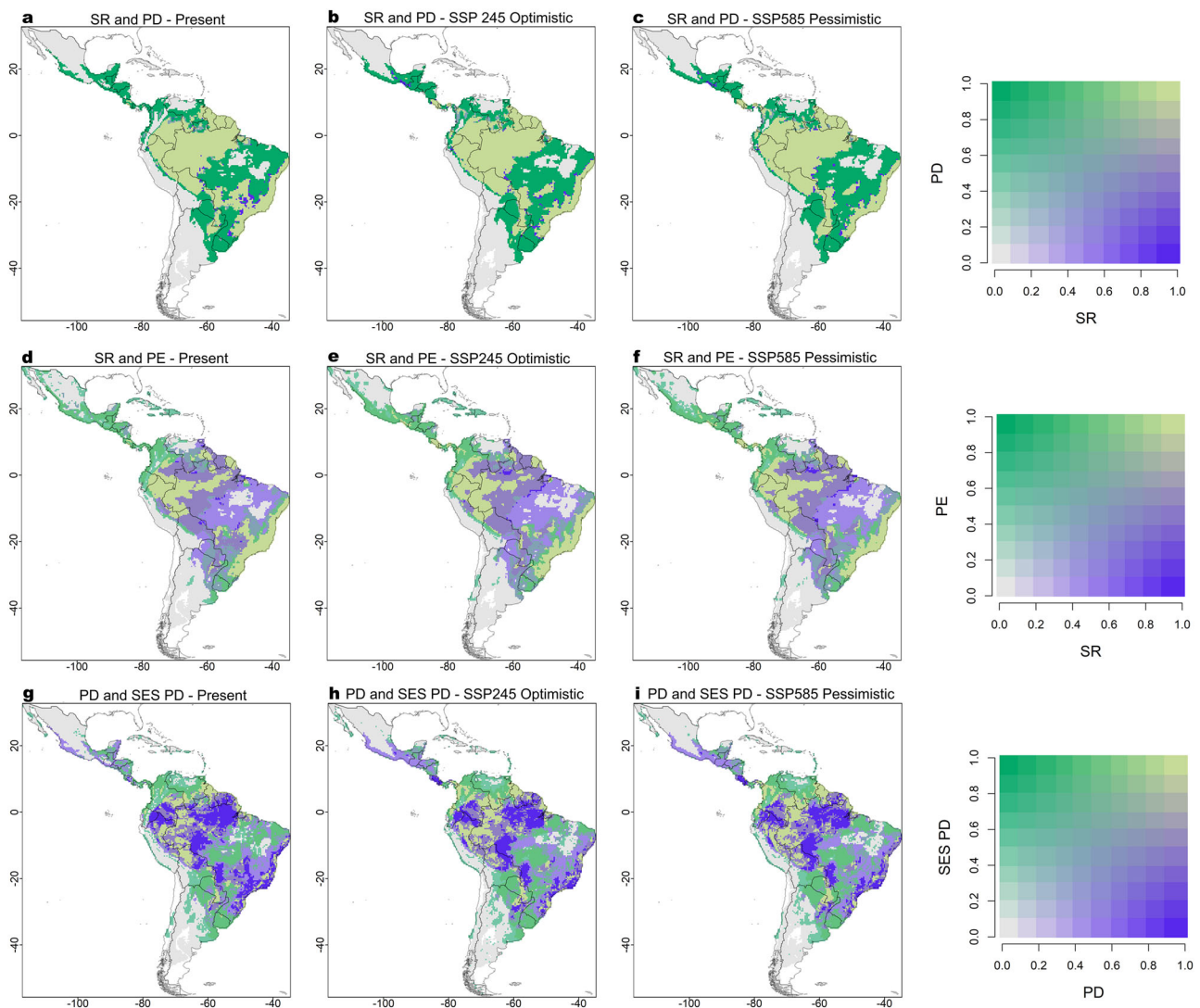


Fig. 4 | Bivariate maps illustrating the relationship between species richness (SR), phylogenetic diversity (PD), phylogenetic endemism (PE), and standardized effect size of PD (SES PD) of 497 Neotropical toads and treefrogs. a SR and PD for the present scenario. **b** SR and PD for the optimistic 2050 scenario. **c** SR and PD for the pessimistic 2050 scenario. **d** SR and PE for the present scenario. **e** SR and PE for the optimistic 2050 scenario. **f** SR and PE for the pessimistic 2050 scenario.

g PD and SES PD for the present. **h** PD and SES PD for the optimistic 2050 scenario. **i** PD and SES PD for the pessimistic 2050 scenario. In (a–i) light green indicates regions where both PD, PE, SR, and SES PD are predicted to be high, gray shows areas where both are predicted to be low, dark green highlights regions where only PD, PE or SES PD is predicted to be high, and purple colors areas where only SR or PD is predicted to be high.

species may change rapidly in the next few years. The rapid onset of these threats requires a more inclusive approach, incorporating predictive models or more ideally observational studies with climate change effects in the last years into the risk assessments to ensure that climate change impacts are adequately represented.

Our results also show that SR and PD of Neotropical frogs are projected to be currently concentrated in two large regions; the first in southeastern Brazil, and the second in northwestern South America. These regions are known to have high SR not just for frogs, but also for other vertebrates such as birds²³, mammals²⁴, and reptiles²⁵. The high diversity of plants and animals may be related to the highly complex biogeographic history of the Neotropics²⁶. Events such as the rise of the Andes, the closure of the Isthmus of Panama, and river formation in Amazon may have shaped the diversity that we see today²³.

Our models suggest that climate change is projected to shift the diversity patterns of Neotropical frogs. Tropical species are expected to show particular sensitivity to climate change, as they typically live near their critical thermal maximum and show fitness declines under

shifting climates²⁷. However, temperature is not the only factor determining species distribution²⁸ and other climate variables, such as precipitation regimes or water balance, may also be closely related to species range shifts²⁸. Our results support this, as the models showed that precipitation of driest quarter (BIO 17) and annual precipitation (BIO 12) are the main drivers of range shifts for toads. These organisms can be strongly affected by drought because they are dependent on water availability for reproduction²⁹. Even for species with direct development, which do not deposit their eggs directly in water, the risk of water loss through evaporation is among the greatest threats to embryo development³⁰.

If species are able to change their distributions in the future, novel communities may arise, possibly holding low SR, low functional and genetic diversity. Our models projected a marked decrease in SR and PD in the Guiana Shield, southeastern Brazil, east Amazonia, and the northern Andes. The projected impact of climate change on evolutionarily distinct taxa¹¹ leads to phylogenetic homogenization of future communities^{31,32} and reduction in the

ecosystem services provided by those species³¹. Frogs can provide different services for human society, including provisioning, regulating (e.g., predation of insects and prey population regulations), cultural (e.g., mythology, literature, and art), and supporting services (e.g., ecosystem functions)³³.

By 2050, the western Amazon and some parts of the Atlantic Rainforest are predicted to hold or even experience an increase in SR and PD of Neotropical frogs. These regions represent areas of higher importance for conservation as they are inhabited by a high number of species, including birds, reptiles, mammals^{23–25,34}, and our projections indicate that the Neotropical frog diversity will be maintained there in the future. Despite their high priority for conservation, the Amazon and the Atlantic Rainforest are also the world's most threatened regions in the world and are losing natural habitats due to urbanization and extensive deforestation^{35,36}.

The spatial patterns of PE for Neotropical frogs are also predicted to shift under climate change. Regions with geographically rare and evolutionary distinct lineages (PE hotspots) in the Amazon, south-eastern Brazil, Guiana Shield, and Southern Mexico are projected to suffer substantial decreases in the future. These PE hotspots may host species with distinct trait diversity and possibly represent regions predicted to maximize ecosystem functions^{12,37}. PE is predicted to increase in northwestern and southeastern Colombia and in the northern Guiana Shield in the future, due to the reductions in the distributions of phylogenetically distinct lineages. As PE is considered a measure of rarity, it should increase in regions where the remaining distribution of the species are concentrated¹⁰.

Our models show that some centers of high PE are not areas of particularly high SR or high PD, such as the Caribbean Islands (Cuba, Haiti, Jamaica, Dominican Republic, and The Bahamas). These areas have one characteristic in common: geographic isolation. The spatial isolation is considered an important predictor of centers of endemism and can provide the conditions for diversification and maintenance of range-restricted clades³⁸. Geographic barriers can favor the maintenance of these clades through vicariance forces, and speciation processes, mainly through allopatric speciation and reduction in gene flow. These islands are known for also harboring high endemism for other groups, such as mammals³⁸, birds³⁹, and reptiles³⁹.

Our analyses predict regions where frog diversity may be overlooked when solely considering SR. There are important areas for the conservation of the phylogenetic component (higher PD and SES PD) in southeastern and northern Brazil, southern Paraguay, northern Bolivia, northeastern Peru, eastern Colombia, southern Venezuela, and northern Guyana. Similarly, Caribbean Islands, Mexico, and northern Colombia demonstrate elevated PE despite their relatively low SR. In fact, biodiversity metrics can vary across space and show high spatial incongruence due to different mechanisms that affect the relationship between diversity metrics³⁷. For instance, the phylogenetic tree topology and the number of highly distinct species shape the relationship between SR and PD, and tend to decrease the correlation between these metrics³⁷. Therefore, considering the spatial inconsistencies between diversity metrics, approaches that weight species by their phylogenetic contributions or endemism can offer best case scenarios for decision makers^{31,37}.

With the advance of climate change, species are predicted to experience novel climatic conditions and will have to adapt or shift their distribution to newly inhabited environments⁴⁰. Range shift in response to climate change is a dynamic process affected by different mechanisms, such as migration, gene flow, novel communities, and new biotic interactions. Limits in dispersal and migration may reduce the capacity of species to track climatically suitable conditions⁴⁰. Biotic interactions such as competition and consumption/predation can also prevent the establishment of new populations at novel range limits⁴¹. For example, if a required prey is not present in the novel area, a species may not be able to expand their range boundaries; likewise

species can be excluded from some regions due to competitive interactions with new community members⁴¹. Therefore, there are ecological and evolutionary processes arising in non-equilibrium situations that may limit, or in some cases possibly accelerate, range expansions. As limited data exist to evaluate the potential importance of these mechanisms in our predictions, this is an added component of model uncertainty.

Our forecasts, like any empirical model, contain a certain amount of uncertainty. This uncertainty arises from the data observation process and our modeling assumptions. For example, we assume that climate variation within current ranges is a reasonable approximation of the species future requirements and that species will respond to climate change by occupying emerging areas compatible with identified niche constraints and that are accessible according to identified migration rates. Substitution of space for time can break down, especially in highly under-parameterized models⁴². The assumption of niche conservatism disregards the ability of species to persist through adaptation and plasticity when confronted with novel conditions⁴³. If non-analog climatic conditions appear in the future and replace the present climate combinations, species will decline their range area due to a purely statistical phenomenon, because our models do not account for acclimatization, plasticity, or adaptation. Nonetheless, we believe that our models are sufficiently flexible to capture the species-climate relationships needed for forecasting, as has been demonstrated in previous studies^{44,45}.

We predicted that at least 42.20% of toads and treefrogs will lose range in the future due to climate change. At first glance, this result does not seem so alarming because the percentage of species gaining range area is higher than the percentage of species losing range area²⁰. However, our database covers only 19% of all Neotropical frogs due to lack of occurrence data for many species. The low number of species we were able to include in our study certainly underestimates the effect of climate change on Neotropical frogs, because many of the species excluded from our study have highly restricted distributions and are already classified as threatened by IUCN²⁰. For example, many species from the genus *Atelopus* and *Melanophryniscus* are already threatened, but are data deficient in terms of their distribution. The continued documentation of species occurrences through field work is a key step to guarantee a representative assessment of climate change effects on a higher number of frog species, especially for endemic and threatened species.

Few studies this far have addressed how future climate change may affect the PE of Neotropical frogs. Our models predict that northwestern and southeastern Colombia and northern Guiana Shield are predicted to hold a high PE in the future, becoming an important refugium for species with deep evolutionary histories and restricted distribution. In contrast, other important hotspots of biodiversity are predicted to lose PE. This result highlights the need of an integrative approach to conservation forecasting, that considers both SR and phylogenetic information to assure the conservation of frog evolutionary history and provides best-case scenarios for managers in the future^{31,37}. The conservation of species with distinct genetic heritage provides high potential for future adaptation to non-analogous climatic conditions caused by global warming.

Methods

Data gathering

Using SDMs we constructed potential distribution maps for 526 Neotropical frogs in the families Bufonidae (toads) and Hylidae (treefrogs). Species with a minimum of seven occurrence records were selected. The number of evaluated species represents 22% of all Bufonidae species and 33% of Neotropical Bufonidae species. For Hylidae, the number of evaluated species represents 35% of all Hylidae species and 39% of Neotropical Hylidae species. These two families were selected because they are highly speciose in the Neotropics and because they

include a large number of species currently classified as threatened (~32%, 440 species) according to the IUCN²⁰. The taxonomic names are available in Supplementary Data 1. Anuran occurrence records were obtained using the Global Biodiversity Information Facility (GBIF⁴⁶). See details on occurrence filtering in the Supplementary Methods.

Bioclimatic variables were obtained from the WorldClim database v2.1⁴⁷ with a spatial resolution of 2.5 min (~5 km²) for the baseline (1970–2000, hereafter called present) and for the future (2050). To reduce problems with collinearity between environmental variables, we calculated a correlation matrix using Pearson's coefficient and selected variables with $r < 0.75$ for use in model calibration. For future projections, we selected three global circulation models: CCSM4, MPI-ESM-LR, and MIROC6, and calculated a weighted mean of the three GCMs. We projected future climate models using two Shared Socio-economic Pathways: SSP245, considered an optimistic scenario for the emission of greenhouse gasses, in which emission should start decreasing from 2040 and SSP585, considered a pessimistic scenario, with CO₂ emission levels decreasing only after 2080.

Species distribution models

We followed the Overview, Data, Model, Assessment, and Prediction standardized protocol⁴⁸ to describe the methodology for the SDMs. In this section, we provide a summary of the 'overview' component, while detailed information on each modeling step is available in the Supplementary Methods. The calibration area was based on the minimum convex polygon (MCP), constructed using 100% of the filtered occurrence points, surrounded by a 1.5° (~150 km² at the equator) buffer. This area is typically defined based on the species' accessible region, known as M in the Biotic, abiotic, and movement framework, which considers the region where the species could have dispersed to and colonized over a relevant time period⁴⁹. The MCP and buffer were first made using the 'ENMwizard' package (v0.4.2)⁵⁰ and then models were calibrated with the present climate scenario (1970–2000). To assess the impact of future climate change on the potential distribution of frogs, SDMs were built combining the occurrence records and bioclimatic variables, using the MaxEnt algorithm (v3.4.1)^{51,52} through the 'ENMwizard' package (v0.4.2)⁵⁰. To avoid over-fitting, we conducted a grid-search for the optimal hyper-parameters based on cross-validated performance measures. See details on model calibration and model selection in the Supplementary Methods.

We projected the best models for each species for three climatic scenarios (present, 2050 optimistic and 2050 pessimistic) to the extension limits of the Neotropics. We converted potential continuous distributions of each species into a presence/absence distribution (1 = presence and 0 = absence) applying the cut-off threshold of 10%. This is a relatively conservative threshold, which typically results in a larger estimated area of occupancy than the actual one. However, it has a low likelihood of omitting true presence points, thereby helping to reduce the overestimation of species range. SDMs often identify large range areas that have not yet been and possibly will never be colonized by the species due to dispersal limitations. To address this overprediction, we used a distance constraint layer based on species dispersal abilities to crop the presence/absence models. See details on overprediction removal and how we defined species dispersal abilities in the Supplementary Methods.

Species richness, phylogenetic diversity, and phylogenetic endemism

Species richness (SR) was calculated using the sum of presence/absence maps following the Eq. (1) using the package 'phyloraster' (v2.1)⁵³,

$$SR = \sum_{c \in C} S_c \quad (1)$$

where S_c is the presence of species c and C is the set of species in a specific region. We calculated the percentage change (PC) in the range area of each species by subtracting the area in the future from the area in the present and multiplying this value by 100 following the Eq. (2),

$$PC = \frac{(F_i - P_i)}{P_i} * 100 \quad (2)$$

where F_i represents the area in the future for the species i and P_i represents the area in the present for the species i . We assessed the correlation between the percentage change in range area and the current range size. Additionally, we tested whether the mean increase and decrease in range area differ significantly. See details on range area analysis in the Supplementary Methods.

We used the phylogenetic tree of Portik et al.⁵⁴ to assess phylogenetic relationships among species. This time-calibrated phylogeny includes 5242 anuran species, with data from 307 genetic markers, and was constructed using maximum-likelihood analysis⁵⁴. See details on branch length calculations in the Supplementary Methods. Based on the distribution models converted to a presence/absence distribution and the anuran phylogenetic tree⁵⁴, we calculated PD¹¹ and PE^{12,13} for the present and the future using the function `geo.phylo` in the package 'phyloraster' (v2.1)⁵³. PD uses the sum of the branch lengths of a set of species in a given region to assess their accumulated evolutionary history and was calculated following the Eq. (3)¹¹,

$$PD = \sum_{c \in C} L_c \quad (3)$$

where L_c is the branch lengths of species c and C are the branches in a specific region. To assess the relationship between SR and PD, we fitted a spatial autoregressive (SAR) model. We used null-models to assess whether PD is lower or higher than expected on the basis of SR. See details on SAR models and null models in the Supplementary Methods.

PE weights the sum of the length of the branches by the inverse of range size of the species to identify regions with high spatially restricted PD, and was calculated following the Eq. (4)

$$PE = \sum_{c \in C} L_c \frac{r_c}{R_c} \quad (4)$$

where L_c is the branch length of taxon c , r_c is the local range of branch c , and R_c is the range area of the clade. C are the branches in a specific region. To assess the magnitude and direction of the impacts of climate change on SR, PD, and PE we calculated the spatial difference (delta) between these metrics for present and future scenarios in 'phyloraster' (v2.1)⁵³. We also made bivariate maps illustrating the relationship between SR, PD, and PE using the 'bivariateplots' R package (v1.7)⁵⁵.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data generated in this study are provided in the Supplementary Information. Anuran occurrence records were obtained using the Global Biodiversity Information Facility (GBIF⁴⁶). Bioclimatic variables were obtained from the WorldClim database v2.1⁴⁷. Source Data is provided in the Source Data File. Source data are provided with this paper.

Code availability

The codes supporting the findings of this study have been deposited in Zenodo⁵⁶.

References

- Intergovernmental Panel On Climate Change (Ippc). *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. <https://doi.org/10.1017/9781009325844> (Cambridge University Press, 2023).
- Brook, B. W., Sodhi, N. S. & Bradshaw, C. J. A. Synergies among extinction drivers under global change. *Trends Ecol. Evol.* **23**, 453–460 (2008).
- Nunez, S., Arets, E., Alkemade, R., Verwer, C. & Leemans, R. Assessing the impacts of climate change on biodiversity: is below 2 °C enough? *Climatic Change* **154**, 351–365 (2019).
- Jetz, W., Wilcove, D. S. & Dobson, A. P. Projected impacts of climate and land-use change on the global diversity of birds. *PLoS Biol.* **5**, e157 (2007).
- Powers, R. P. & Jetz, W. Global habitat loss and extinction risk of terrestrial vertebrates under future land-use-change scenarios. *Nat. Clim. Chang.* **9**, 323–329 (2019).
- Sales, L. P., Rodrigues, L. & Masiero, R. Climate change drives spatial mismatch and threatens the biotic interactions of the Brazil nut. *Glob. Ecol. Biogeogr.* **30**, 117–127 (2021).
- Hof, C., Araújo, M. B., Jetz, W. & Rahbek, C. Additive threats from pathogens, climate and land-use change for global amphibian diversity. *Nature* **480**, 516–519 (2011).
- Alves-Ferreira, G., Talora, D. C., Solé, M., Cervantes-López, M. J. & Heming, N. M. Unraveling global impacts of climate change on amphibians distributions: a life-history and biogeographic-based approach. *Front. Ecol. Evol.* **10**, 987237 (2022).
- Mishler, B. D. et al. Phylogenetic measures of biodiversity and neo- and paleo-endemism in Australian *Acacia*. *Nat. Commun.* **5**, 4473 (2014).
- González-Orozco, C. E. et al. Phylogenetic approaches reveal biodiversity threats under climate change. *Nat. Clim. Change* **6**, 1110–1114 (2016).
- Faith, D. P. Conservation evaluation and phylogenetic diversity. *Biol. Conserv.* **61**, 1–10 (1992).
- Rosauer, D., Laffan, S. W., Crisp, M. D., Donnellan, S. C. & Cook, L. G. Phylogenetic endemism: a new approach for identifying geographical concentrations of evolutionary history. *Mol. Ecol.* **18**, 4061–4072 (2009).
- Laffan, S. W. et al. Range-weighted metrics of species and phylogenetic turnover can better resolve biogeographic transition zones. *Methods Ecol. Evol.* **7**, 580–588 (2016).
- Elith, J. & Franklin, J. Species distribution modeling. In *Encyclopedia of Biodiversity* 692–705. <https://doi.org/10.1016/B978-0-12-384719-5.00318-X> (Elsevier, 2013).
- Thuiller, W. et al. Consequences of climate change on the tree of life in Europe. *Nature* **470**, 531–534 (2011).
- Huang, S., Davies, T. J. & Gittleman, J. L. How global extinctions impact regional biodiversity in mammals. *Biol. Lett.* **8**, 222–225 (2012).
- Luedtke, J. A. et al. Ongoing declines for the world's amphibians in the face of emerging threats. *Nature* **622**, 308–314 (2023).
- Zeisset, I. & Beebee, T. J. C. Amphibian phylogeography: a model for understanding historical aspects of species distributions. *Heredity* **101**, 109–119 (2008).
- Bolanos, F. et al. in *Threatened Amphibians of the World* (eds Stuart, S. N. et al.) 92–105 (Lynx Edicions and IUCN and Conservation International, 2008).
- IUCN. The IUCN Red List of Threatened Species. Version 2023-1 (Accessed 12 December 2024). <https://www.iucnredlist.org> (2023).
- Mantyka-pringle, C. S., Martin, T. G. & Rhodes, J. R. Interactions between climate and habitat loss effects on biodiversity: a systematic review and meta-analysis. *Glob. Change Biol.* **18**, 1239–1252 (2012).
- Lötters, S. et al. Ongoing harlequin toad declines suggest the amphibian extinction crisis is still an emergency. *Commun. Earth Environ.* **4**, 412 (2023).
- Rangel, T. F. et al. Modeling the ecology and evolution of biodiversity: biogeographical cradles, museums, and graves. *Science* **361**, eaar5452 (2018).
- Loiseau, N. et al. Global distribution and conservation status of ecologically rare mammal and bird species. *Nat. Commun.* **11**, 5071 (2020).
- Böhm, M. et al. The conservation status of the world's reptiles. *Biol. Conserv.* **157**, 372–385 (2013).
- Rull, V. & Carnaval, A. C. *Neotropical Diversification: Patterns and Processes*. <https://doi.org/10.1007/978-3-030-31167-4> (Springer International Publishing, Cham, 2020).
- Deutsch, C. A. et al. Impacts of climate warming on terrestrial ectotherms across latitude. *Proc. Natl. Acad. Sci. USA*. **105**, 6668–6672 (2008).
- Lawlor, J. A. et al. Mechanisms, detection and impacts of species redistributions under climate change. *Nat. Rev. Earth Environ.* **5**, 351–368 (2024).
- Wells, K. D. *The Ecology and Behavior of Amphibians* (The University of Chicago Press, USA, 2007).
- Walls, S., Barichivich, W. & Brown, M. Drought, deluge and declines: the impact of precipitation extremes on amphibians in a changing climate. *Biology* **2**, 399–418 (2013).
- Borges, F. J. A., Fortunato, D. D. S. & Loyola, R. Critical areas for retaining multiple dimensions of bird diversity in the Cerrado. *J. Nat. Conserv.* **64**, 126079 (2021).
- Hidasi-Neto, J. et al. Climate change will drive mammal species loss and biotic homogenization in the Cerrado Biodiversity Hotspot. *Perspect. Ecol. Conserv.* **17**, 57–63 (2019).
- Hocking, D. J. & Babbitt, K. J. Amphibian contributions to ecosystem services. *Herpetol. Conserv. Biol.* **9**, 1–17 (2014).
- Menéndez-Guerrero, P. A., Green, D. M. & Davies, T. J. Climate change and the future restructuring of Neotropical anuran biodiversity. *Ecography* **43**, 222–235 (2020).
- Laurance, W. F. & Vasconcelos, H. L. Consequências ecológicas da fragmentação florestal na Amazônia. *Oecol. Bras.* **13**, 434–451 (2009).
- Vancine, M. H. et al. The Atlantic Forest of South America: spatio-temporal dynamics of the vegetation and implications for conservation. *Biol. Conserv.* **291**, 110499 (2024).
- Cadotte, M. W. & Tucker, C. M. Difficult decisions: Strategies for conservation prioritization when taxonomic, phylogenetic and functional diversity are not spatially congruent. *Biol. Conserv.* **225**, 128–133 (2018).
- Rosauer, D. F. & Jetz, W. Phylogenetic endemism in terrestrial mammals. *Glob. Ecol. Biogeogr.* **24**, 168–179 (2015).
- Kier, G. et al. A global assessment of endemism and species richness across island and mainland regions. *Proc. Natl. Acad. Sci. USA*. **106**, 9322–9327 (2009).
- Spence, A. R. & Tingley, M. W. The challenge of novel abiotic conditions for species undergoing climate-induced range shifts. *Ecography* **43**, 1571–1590 (2020).
- HilleRisLambers, J., Harsch, M. A., Ettinger, A. K., Ford, K. R. & Theobald, E. J. How will biotic interactions influence climate change-induced range shifts? *Ann. N. Y. Acad. Sci.* **1297**, 112–125 (2013).
- Perret, D. L., Evans, M. E. K. & Sax, D. F. A species' response to spatial climatic variation does not predict its response to climate change. *Proc. Natl. Acad. Sci. USA*. **121**, e2304404120 (2024).
- Araújo, M. B., Thuiller, W. & Pearson, R. G. Climate warming and the decline of amphibians and reptiles in Europe. *J. Biogeogr.* **33**, 1712–1728 (2006).
- Yannic, G. et al. Genetic diversity in caribou linked to past and future climate change. *Nat. Clim. Change* **4**, 132–137 (2014).

45. Franklin, J. Species distribution modelling supports the study of past, present and future biogeographies. *J. Biogeogr.* **50**, 1533–1545 (2023).
 46. GBIF.org. GBIF Occurrence Download. <https://doi.org/10.15468/dl.dv9ju3> (2024).
 47. Fick, S. E. & Hijmans, R. J. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.* **37**, 4302–4315 (2017).
 48. Zurell, D. et al. A standard protocol for reporting species distribution models. *Ecography* **43**, 1261–1277 (2020).
 49. Barve, N. et al. The crucial role of the accessible area in ecological niche modeling and species distribution modeling. *Ecol. Model.* **222**, 1810–1819 (2011).
 50. Heming, N. M., Dambros, C. & Gutiérrez, E. E. ENMwizard: advanced techniques for ecological niche modeling made easy. v 0.4.2. <https://github.com/HemingNM/ENMwizard> (2018).
 51. Phillips, S. J., Anderson, R. P., Dudík, M., Schapire, R. E. & Blair, M. E. Opening the black box: an open-source release of Maxent. *Ecography* **40**, 887–893 (2017).
 52. Phillips, S. J., Anderson, R. P. & Schapire, R. E. Maximum entropy modeling of species geographic distributions. *Ecol. Model.* **190**, 231–259 (2006).
 53. Alves-Ferreira, G. et al. phyloraster: an R package to calculate measures of endemism and evolutionary diversity for rasters. *Ecography* **2024**, e06902 (2024).
 54. Portik, D. M., Streicher, J. W. & Wiens, J. J. Frog phylogeny: a time-calibrated, species-level tree based on hundreds of loci and 5,242 species. *Mol. Phylogenet. Evol.* **188**, 107907 (2023).
 55. Hidasi-Neto, J. bivariate maps: Creates bivariate maps. v 1.7. <https://doi.org/10.32614/CRAN.package.bivariate maps> (2024).
 56. Alves-Ferreira, G. et al. gabferreira/phylo_endemism_frogs: Data from: Climate change is projected to shrink phylogenetic endemism of Neotropical frogs (v1.0.0). *Zenodo*. <https://doi.org/10.5281/zenodo.15015040> (2025).
- editing (supporting). D.C.T.: Conceptualization (supporting); Supervision (supporting); Validation (supporting); Visualization (supporting); Methodology (equal); Writing – review and editing (supporting). T.H.K.: Conceptualization (supporting); Validation (supporting); Methodology (equal); Visualization (supporting); Writing – review and editing (supporting). M.S.: Supervision (supporting); Methodology (equal); Validation (supporting); Visualization (supporting); Writing – review and editing (supporting). K.R.Z.: Conceptualization (supporting), Supervision (supporting), Methodology (equal), Validation (supporting); Visualization (supporting); Writing – original draft (lead); Writing – review and editing (lead).

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41467-025-59036-2>.

Correspondence and requests for materials should be addressed to Gabriela Alves-Ferreira.

Peer review information *Nature Communications* thanks Gentile Francesco Ficetola and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. A peer review file is available.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025

Acknowledgements

G.A.-F. was supported by a doctoral fellowship and a scholarship of the Programa de Doutorado-sanduiche no Exterior (PDSE) funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) during the preparation of this study (001) and NMH by a CAPES post-doctoral fellowship (#88882.314922/2019-01). G.A.-F. also thanks Idea Wild for donating equipment used to develop this article. This work was supported by the project approved by the Pró-Reitoria de Pesquisa e Pós-Graduação (PROPP) – UESC (0731101020220030757-31).

Author contributions

G.A.-F.: Conceptualization (lead); Data curation (lead); Methodology (lead); Software (equal); Validation (lead); Visualization (lead); Writing – original draft (lead); Writing – review and editing (lead). N.M.H.: Conceptualization (supporting); Methodology (equal); Software (equal); Supervision (supporting); Validation (supporting); Writing – review and