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Efeitos das mudanças climáticas nos padrões de diversidade alfa e beta de anuros do Cerrado

ILHÉUS - BAHIA
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Dissertação apresentada à Universidade Estadual de Santa Cruz, como parte das exigências para obtenção do título de Mestre em Ecologia e Conservação da Biodiversidade.

Área de concentração: Ecologia e conservação de comunidades

Orientador: Profª. Daniela Talora
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Ilhéus, 19 de Fevereiro de 2024.

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Efeitos das mudanças climáticas nos padrões de diversidade alfa e beta de anuros do Cerrado

RESUMO

As mudanças climáticas representam uma ameaça significativa à biodiversidade, afetando a distribuição e a composição das espécies. No Cerrado, uma savana brasileira ameaçada, as projeções de mudanças climáticas indicam aumento das temperaturas e diminuição da precipitação, o que pode afetar a distribuição dos anuros. Assim, o principal objetivo deste estudo foi avaliar o impacto das mudanças climáticas na diversidade alfa (riqueza de espécies) e beta (mudança de composição) dos anuros do Cerrado. Além disso, examinamos a relação entre as mudanças na diversidade e as variáveis climáticas (anomalia climática, velocidade da mudança climática, precipitação anual atual e temperatura média anual), a fim de avaliar o impacto dessas métricas climáticas na diversidade de anuros futura. Utilizamos dados de ocorrência de 139 espécies de anuros e técnicas de modelagem de nicho ecológico (ENM) para projetar a distribuição das espécies nos cenários climáticos atual e futuro (2050). Usamos cenários pessimistas de concentração de gases de efeito estufa. Calculamos a diversidade alfa e beta, e avaliamos os efeitos das anomalias de temperatura e precipitação nas métricas de diversidade. Nossos resultados mostraram um declínio na riqueza de espécies de anuros na maior parte do Cerrado, com as regiões sudeste e sudoeste apresentando as maiores perdas. As regiões norte e nordeste apresentaram ganhos na riqueza de espécies. A reestruturação das comunidades de anuros foi impulsionada principalmente pela substituição de espécies, afetando as porções noroeste, oeste e leste do bioma. As análises de regressão indicaram que a maior anomalia nos extremos de temperatura, a maior velocidade de mudança e a temperatura atual tendem a causar perda ou menor ganho de espécies, enquanto a maior anomalia na precipitação tende a causar maior ganho de espécies. O efeito dos preditores climáticos na diversidade beta indicou que valores mais baixos de anomalia de precipitação e aumentos nos extremos de temperatura levam a maiores mudanças na composição das espécies. Nosso estudo fornece informações alarmantes sobre a perda de espécies e a reestruturação das comunidades de anuros no Cerrado, sugerindo uma diminuição significativa na diversidade de espécies na maior parte do bioma. Esses resultados destacam os possíveis impactos das mudanças climáticas sobre a diversidade de anuros no Cerrado e enfatizam a necessidade de estratégias de conservação para mitigar os efeitos das mudanças climáticas sobre espécies e ecossistemas vulneráveis.

Palavras-chave: Anura; estrutura da comunidade; distribuição de espécies; área adequada; modelagem de nicho ecológico; aquecimento global.

Efeitos das mudanças climáticas nos padrões de diversidade alfa e beta de anuros do Cerrado

ABSTRACT

Climate change poses a significant threat to biodiversity, impacting species distribution and composition. In the Cerrado, a threatened Brazilian savanna, climate change projections indicate increased temperatures and decreased precipitation, potentially impacting anuran's distribution. Therefore, our main goal was to evaluate the impact of climate change on alpha (species richness) and beta diversity (composition change) of Cerrado anurans. Additionally, we examined the relationship between diversity changes and climatic variables (climate anomaly, velocity of climate change, current annual precipitation and annual mean temperature), in order to assess the impact of these climate metrics on future diversity. We used occurrence data from 139 anuran species, and ecological niche modeling (ENM) techniques to project species distributions under the current (baseline) and future climate scenarios (2050). We used pessimistic greenhouse gas concentration scenarios. We calculated alpha and beta diversity, and evaluated the effects of temperature and precipitation anomalies on the diversity metrics. Our results showed a decline in anuran species richness in most of the Cerrado, with the southeast and southwest regions experiencing the highest losses. The north and northeast regions showed gains in species richness. The restructuring of anuran communities was primarily driven by species replacement, affecting the northwest, west, and east portions of the biome. Regression analyses indicated that higher anomaly in the temperature extremes, higher velocity of change and current temperature tends to cause loss or lower species gain, while higher anomaly in the precipitation tends to cause higher species gains. The effect of climatic predictors on beta diversity indicated that lower precipitation anomaly values and increases in temperature extremes lead to greater changes in species composition. Our study provides alarming information regarding species loss and restructuring of anuran communities in the Cerrado, suggesting a significant decrease in species diversity across most of the biome. These findings highlight the potential impacts of climate change on anuran diversity in the Cerrado and emphasize the need for conservation strategies to mitigate the effects of climate change on vulnerable species and ecosystems.

Keywords: Anura; community structure; species distribution; suitable area; ecological niche modeling; global warming.

SUMÁRIO

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Climate change effects on alpha and beta diversity patterns of Cerrado anurans

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ABSTRACT

Aim: Climate change poses a significant threat to biodiversity, impacting species distribution and composition. In the Cerrado, a threatened Brazilian savanna, climate change projections indicate increased temperatures and decreased precipitation, potentially impacting anuran's distribution. We evaluated the impact of climate change on alpha (richness) and beta diversity of Cerrado anurans. Additionally, we examined the relationship between diversity changes and climatic variables (climate anomaly, velocity of climate change, current annual precipitation and annual mean temperature), in order to assess the impact of these climate metrics on future diversity.

Location: Cerrado, Brazil.

Methods: We used occurrence data from 139 anuran species, and ecological niche modeling (ENM) techniques to project species distributions under the current (baseline) and future climate scenarios (2050). We used pessimistic greenhouse gas concentration scenarios. We calculated alpha diversity (species richness) and beta diversity (composition change), and evaluated the effects of temperature and precipitation anomalies on the diversity metrics.

Results: Our results showed a decline in anuran species richness in most of the Cerrado, with the southeast and southwest regions experiencing the highest losses. The north and northeast regions showed gains in species richness. The restructuring of anuran communities was primarily driven by species replacement, affecting the northwest, west, and east portions of the biome. Regression analyses indicated that higher anomaly in the temperature extremes, higher

velocity of change and current temperature tends to cause loss or lower species gain, while higher anomaly in the precipitation tends to cause higher species gains. The effect of climatic predictors on beta diversity indicated that lower precipitation anomaly values and increases in temperature extremes lead to greater changes in species composition.

Main conclusions: Our study provides alarming information regarding species loss and restructuring of anuran communities in the Cerrado, suggesting a significant decrease in species diversity across most of the biome. These findings highlight the potential impacts of climate change on anuran diversity in the Cerrado and emphasize the need for conservation strategies to mitigate the effects of climate change on vulnerable species and ecosystems.

Keywords: Anura; community structure; species distribution; suitable area; ecological niche modeling; global warming.

INTRODUCTION

Climate is one of the main determining factors of species distribution (Guisan and Thuiller, 2005; Svenning and Skov, 2007) and consequently, a key driver of current richness patterns (Liu et al., 2017). Climate change, mediated by human activity, represents a threat to biodiversity (Nunez et al., 2019) and can lead to changes in the physiology, life cycle, and distribution of species (Lawson et al., 2015; Pecl et al., 2017). The risk of species extinction in the future is not only expected to increase, but is also predicted to accelerate as global temperatures rise (Urban, 2015). Large rearrangements in species distribution are predicted to occur due to climate change, as the climatically suitable area for a determined species can be expanded, contracted, moved to new areas, or even lost entirely (Early and Sax, 2011; Lenoir and Svenning, 2015; Li et al., 2013; Ochoa-Ochoa et al., 2012). Shifts in species distribution due to climate change may impact biological communities due to species loss as well as to the redistribution and establishment of new species, both with consequences on diversity patterns (Ochoa-Ochoa et al., 2012).

Changes in climate can be measured in many ways because different metrics capture distinct dimensions of climate change. These metrics include climate anomaly, differences in extreme events and velocity of climate change (Garcia et al., 2014b). Climate anomaly is given by the Euclidean distance between the baseline and future climate at a given location, standardized by historical interannual climate variability. Temporal differences in the frequency extreme events, such as extreme droughts, precipitation, or temperatures may

influence biotic interactions, biodiversity, and ecosystem functioning pushing species to their limits (Coumou and Rahmstorf, 2012; Garcia et al., 2014b; Harris et al., 2018; Thakur et al., 2022). Therefore, this metric can reveal where populations may potentially be most threatened. Climate change velocity is a measure of climatic dislocation rate in the landscape (Garcia et al., 2014b). Rapid changes further increase the risk of extinction since species would need to keep pace with climate as they move to pursue their suitable climates (Loarie et al., 2009; Pearson, 2006), and rapidly acquire the ability to adjust through migration and colonization (Williams et al., 2007).

Climate change is unlikely to affect all areas equally, and some regions may experience a much more pronounced climate anomaly, as pointed out for the north and northwest region of Cerrado (Borges and Loyola, 2020), an extremely threatened Brazilian savanna. The biome is expected to become hotter (increase of 2.0ºC) and dryer (15% reduction in humidity) by 2050 (Hofmann et al., 2021). Cerrado occupies approximately 23% of Brazil's land area and is considered a global biodiversity hotspot due to the intense effects of habitat loss and the high degree of endemism that the biome supports (Myers et al., 2000). The biome suffers strong agricultural pressure and is located in a region expected to present high future climate instability (Borges et al., 2019), which can make it even more difficult for species to move and be able to keep up with climate change velocity.

The ecological niche and its amplitude are established in environmental terms by the climatic properties that influence the conditions for the occurrence of species (Mayr, 2009). Niche models based on environmental predictors yield projections of potential habitats for species (Guisan and Zimmermann, 2000), an approximation to the species' fundamental niche (Soberon and Peterson, 2005). Ecological niche models (ENM) have been useful for predicting the effects of climate change on the potential distribution of species, as well as generating conservation strategies based on a dynamic climate (Lemes and Loyola, 2013). Particularly, it can be used for predicting spatial change in species richness and composition considering different climate change scenarios (Jones and Cheung, 2015; Loyola et al., 2013). In this sense, projections of species distributions on future climate scenarios can help to understand how the communities will be affected and to assess the magnitude of changes in community structure (Lima et al., 2019; Vasconcelos et al., 2018).

Two simple diversity measures can help in such evaluations: the alpha species diversity and the beta diversity. The alpha diversity can be measured by species richness, which is

calculated as the sum of species in a specific region, while beta diversity measures the change in species composition in a site. There are two different metrics that can produce differences in species composition. The first is the replacement of some species by others, a concept identified as turnover (Baselga, 2012). The second is nestedness, which occurs when sites with smaller numbers of species are subsets of richer sites, characterized by species loss or gain, in this case no species is replaced by another (Baselga, 2010; Cardoso et al., 2015).

Species that present more specific physiological requirements, dependence on a specialized habitat, reduced tolerance to environmental factors, and a limited ability to colonize new favorable areas are more susceptible to experience the negative effects of changes in climate (Ballesteros-Barrera et al., 2022; Parmesan et al., 1999). This susceptibility is especially applicable to amphibians, given their well-documented extreme sensitivity to environmental changes (Alan Pounds et al., 2006; Blaustein et al., 2010). In general, all aspects of amphibians' life history are influenced by the external environment, such as precipitation regimes and temperature (Feder and Burggren, 1992). For instance, they are ectothermic, which means their metabolism is strongly related to environmental temperatures (Ficetola and Maiorano, 2016; Kearney and Porter, 2009).

Amphibians have an amplitude of their thermal tolerance limited by a minimum (CTMin) and a maximum critical temperature (CTMax) and, for tropical species, this upper thermal limit is currently closer to environmental temperatures (Huey et al., 2012, 2009). Therefore, a small increase in temperature may lead these animals to a physiological collapse (Tewksbury et al., 2008). In addition, amphibians may be sensitive to changes in rainfall regime, as they rely on humid environments, require water for reproduction and development, and have peaks of activity and reproduction driven by wet periods (Ficetola and Maiorano, 2016). Thus, weather conditions commonly affect the anurans phenology and distribution (Cayuela et al., 2016). Due to this general context, the diversity of anurans tends to be higher in the regions and biomes with high humidity, high annual precipitation and a high number of aquatic micro-habitats (Vasconcelos et al., 2010). In this sense, the projected drier and hotter conditions of the Cerrado in the future has been a matter of concern for the conservation of this group (Alves-Ferreira et al., 2022a; Vasconcelos et al., 2018).

In face of the potential threat that the climate change represents to the Cerrado anurans, we aimed to: I) evaluate the impact of climate change on alpha (richness) and beta diversity of Cerrado anurans, and identify the regions with higher loss and gain of species, as well as, those

with higher composition changes; II) evaluate the relationship between anuran species richness change and beta diversity with multiple dimensions of climate (climate anomaly, velocity of climate change, annual precipitation and annual mean temperature). We expect that increases in temperature regimes and drier conditions will lead to a shrink in the climatically suitable space for the species, causing reductions in anurans richness in most of the Cerrado biome and leading to strong changes in species composition. Furthermore, we expect that regions that experience more intense temperature increases and precipitation decreases will show the greatest species losses and composition changes in the future. Regarding climate change velocity, the regions where the maximum and minimum temperature will change faster, are expected to present the higher losses in species richness and changes in species composition. Considering that colder and wetter conditions will become rarer and spatially contracted, and species adapted to such conditions are more vulnerable to contraction of their suitable climate space, we also expect that locations that present lower mean temperatures or higher precipitations in the present will be those with the greatest richness losses in the future.

METHODS

Occurrence data

We obtained occurrence data for 139 anuran species from scientific literature (data provided by Vasconcelos et al., 2018) and online database Global Biodiversity Information Facility (GBIF: http://www.gbif.org). We removed duplicates, incomplete and unlikely coordinates using the *scrubr* package (Chamberlain, 2021). In order to reduce spatial autocorrelation and possible geographic biases, we removed records that were within 10 km of each other using the *spThin* optimization algorithm (Aiello-Lammens et al., 2015), performed on the R software (R Core Team, 2023). In total, 15,601 occurrence records were maintained in the database. We consider only species with more than five records to fit the models.

Environmental variables

We downloaded a set of 19 bioclimatic variables from the WorldClim v2.1 platform (Fick and Hijmans, 2017), with a spatial resolution of 2.5 arcminutes (~4.5 km² at the equator), for the current baseline (1970-2000) and future scenario (2041-2060), considering three global circulation models (AOGCMs: CNRM-CM6-1, MIROC6, and MRI-ESM2-0) and two shared socio-economic pathway scenarios, one pessimistic (SSP585) and one optimistic (SSP245). After defining the calibration area for each species (see method below), we estimated the

Pearson's correlation coefficient between the variables from the current time using the "select_vars_b" function from the *ENMwizard* package (Heming *et al.* 2018). To reduce collinearity problems, we only selected variables (those of greater biological relevance) with Pearson correlation less than 0.7, resulting in six bioclimatic variables selected as predictors (BIO1, BIO2, BIO15, BIO17, BIO18 and BIO19) to perform the ecological niche models.

Ecological niche models (ENMs)

We used the filtered occurrence data and the selected bioclimatic variables to predict climatically suitable areas for the 139 species of anurans in the Cerrado. We build ENMs through the MaxEnt algorithm (Phillips et al., 2017) using the *ENMwizard* package (Heming et al. 2019) from R software (R Core Team, 2023). We defined the calibration area for model fitting through a 1.5° buffer around a Minimum Convex Polygon (MCP) involving all occurrence points for each target species (Anderson and Raza, 2010; Barve et al., 2011; Heming *et al.* 2018). To apply a model selection structure, we build 150 models for each species, considering all the possible combinations of Feature classes (FCs): linear (L), product (P), quadratic (Q), hinge (H) and interactions; and Regularization multipliers (RMs) values between 0.5 to 5 (15 FCs x 10 RMs). For validation and evaluation of the predictive ability of the models, we applied two methods of geographic partitioning of occurrence records: 'block' and 'jackknife' using the ENMevaluate_b function of the *ENMwizard* package (Heming et al 2018). Block cross-validation partitions the occurrence points into different blocks for model evaluation and calibration (Roberts et al., 2017), while the jackknife method removes only one point at a time and builds a new model in the absence of that point (Pearson, 2007; Shcheglovitova and Anderson, 2013). We used the jackknife method for species with fewer than 15 occurrence records, while the block method was used for species with more records. We calibrated and evaluated the models with the current baseline climate scenario.

After this procedure, we selected 10% of the models with the best performances, which were chosen based on the lowest omission rate (OR) values and the highest area under the curve (AUC) averages, following the sequential procedure suggested by Boria et al. (Boria et al., 2017). We projected the selected models for the current baseline and future scenarios, considering the year 2050, one pessimistic shared socioeconomic pathway (SSP585) and three GCMs (CNRM-CM6-1, MIROC6, and MRI-ESM2). We calculated the weighted average to combine the results of the selected models for the baseline time and future, including three GCMs, resulting in a consensus model for each species in each scenario. Finally, the continuous

suitability maps were converted into binary maps (with 1 and 0 values, indicating suitable and unsuitable areas, respectively) using the 10 percentile training presence (10ptp) threshold, since the threshold value should be adjusted to the prevalence of presence data (Lobo et al., 2008).

Diversity metrics

We calculated the alpha and beta diversity considering only the baseline and pessimistic scenario, because preliminary analyses indicated that the results are very similar between the optimistic and pessimistic scenarios. We estimated the spatial distribution pattern of alpha diversity (species richness) by summing the overlapping binary maps of species predicted for each scenario (current baseline and future) using the "rast.sr" function from the R package *phyloraster* (Alves-Ferreira et al., 2023). Then, we estimated the temporal change in alpha richness (delta richness), calculating the difference between the richness in the current baseline and in the future scenario, using the "delta.grid" function from the same R package. Positive values of "delta richness" indicate species gain in the future, while negative values indicate species loss. In addition, we calculated temporal beta diversity between the current baseline and the future scenarios (SSP585) using the function "temp.beta" from the *divraster* package (Mota et al., 2023). We partitioned beta diversity into replacement (turnover) and richness difference (nestedness) components (Cardoso et al., 2015) to evaluate which was predominant in determining the beta diversity. Values of beta ratio close to one represent the predominance of species replacement (turnover) and values close to zero indicate predominance of gain/loss of species (nestedness).

Predictors variables

We downloaded monthly weather data for average maximum temperature (°C) and total precipitation (mm) for 1981-2000 and for 2041-2060 (SSP 585) from the WorldClim v2.1 database at the resolution of 2.5 arcmin (Fick and Hijmans, 2017). To quantify the magnitude of local climatic anomalies we calculated the sum of Standardized Euclidean Distances (SED, (Garcia et al., 2014b) using the "ccm" function from the *climetrics* package (Taheri et al., 2023). We calculated the SED for precipitation and maximum temperature individually, between the years 1981-2000 (current baseline scenario) and 2041-2060 (future scenario). High anomaly values indicate high change in local climate (Williams et al., 2007). We also calculated the Distance-based climate change velocity (Garcia et al., 2014b) for the two variables mentioned above using the function "ccm" from the package *climetrics* (Taheri et al.,

2023). Also, we obtained the annual mean temperature (Bio 1) and the annual precipitation (Bio 12) for the baseline scenario from the WorldClim v2.1 (Fick and Hijmans, 2017).

Analysis

To evaluate the relationship of delta richness and beta total with climatic predictors we fit linear models (LM) and simultaneous autoregressive models (SAR). We tested the residuals distribution of the linear model for delta richness and beta total using the function "ad.test" from package *nortest* (Gross and Ligges, 2015) to verify the normality assumptions. We build one model for each response variable (delta richness and beta total) using all predictor variables. In both models, we used the richness of the present baseline scenario as a predictor variable to control for the effect of species that are already in each cell at baseline. We applied an analysis of Variance Inflation Factor (VIFs) using the function 'vif' from package *car* (Fox and Weisberg, 2019) to evaluate if there was multicollinearity between the predictors, but variables were not strongly related (VIFs < 3). In addition, we preliminarily tested the spatial autocorrelation of the data based on the residuals of the linear models applying the Moran I test using the function 'lm.morantest' from package *spdep* (Bivand and Piras, 2015). Positive and significant Moran' I values were obtained. To account for spatial autocorrelation, we applied a simultaneous autoregressive model (SAR) using the function 'spautolm' from the package *spatialreg* (Bivand et al., 2021). We defined the matrix of spatial weights using the function 'knearneigh', with k = 1, that indicates the minimum distance between each cell and at least one neighbor. Using this minimum distance, we created the neighborhoods structure with the function 'knn2nb' and created the spatial weights matrix (Kissling and Carl, 2007) using the function 'nb2listw' from package *spdep* (Bivand and Piras, 2015). All analyses were performed on the R software (R Core Team, 2023).

RESULTS

Our study detected that anuran species richness (alpha diversity) is currently (baseline) higher in the southern portion of Cerrado (Figure 1a), while the northeast region presented lower species richness. Our predictions indicated that most of the Cerrado area will lose species in the future (Figure 1b). The greatest richness losses are predicted specifically for the southeast and southwest regions, areas that currently encompass the highest values of species richness, with losses from 30 to 40 species in some areas (Figure 1c). Gains of anuran species are predicted for the regions north, northeast and for a small portion of the easter Cerrado area,

where expressive richness gain (> 20 species) was predicted (Figure 1c). The anuran species richness range from 11 to 111 species in the baseline scenario, while range from 19 to 108 in future scenarios.

The largest changes in the composition of anurans (beta diversity total) were predicted for the northwest, west and east portion of the biome (blue color; Figure 2a), while we observed low to intermediate beta diversity for the regions north, southwest and south of the Cerrado (red color; Figure 2a). The partitioning of beta diversity in two components (turnover and nestedness) reveal that the community will be shaped predominantly by the turnover of anuran species in most of the biome (values close to one, Figure 2b). Contrarily, the nestedness effect is more likely to be observed for a small portion of east center (values close to zero, Figure 2b), where high gains of species richness were predicted (Figure 1c), as also, in small portions of the southeast and southwest regions, where severe losses of species were predicted.

Our results of regression analyses (Table 1) revealed that minimum temperature anomaly and maximum temperature anomaly had a significant negative effect on the delta richness, indicating that higher anomaly in the temperature extremes tends to cause loss or lower species gain (lower delta values). On the other hand, the precipitation anomaly had a significant positive effect in species richness change (Table 1), i.e. higher anomaly in the precipitation tends to lead to higher species gains. We also observed a significant negative effect of the velocity of change in maximum temperature on the delta richness (Table 1), indicating that higher velocity tends to cause loss or lower species gain (lower delta values). Our results demonstrated that mean annual temperature in the present baseline had a negative effect on the delta richness (Table 1), i.e where the current temperature is warmer it is expected higher loss or lower species gain (lower delta values). We found no significant effects of velocity of change in precipitation, velocity of change in minimum temperature, and mean annual precipitation on change in species richness (Table 1).

We also evaluated the effect of climatic predictors on beta diversity. We found that precipitation anomaly has a negative and significant effect on the beta diversity (Table 1), indicating that higher anomaly leads to lower changes in species composition. On the other hand, the anomaly in temperature extremes (minimum and maximum) has a significant and positive effect on the beta diversity (Table 1). This result indicates that as the anomaly in temperature extremes increases, the greater will be the change in species composition in the future. The speed of changes in precipitation and minimum temperature also had a significant

and negative relation on the beta diversity, as well as mean annual temperature (Table 1). On the other hand, the results demonstrated a significant and positive relation of annual precipitation and beta diversity (Table 1), which indicates that higher annual precipitation values in the present baseline are related to greater changes in anuran composition in the Cerrado.

DISCUSSION

Our study predicted a decline in alpha diversity of Cerrado anurans for the year 2050 concentrated in southeast and southwest regions of the Cerrado with a loss of up to 30 species, while for the north and northeast region, we predicted an increase (gain of up to 20 species) in anuran species richness. Additionally, we observed a high change in the composition of anuran communities from Cerrado for the future, primarily driven by species replacement in most of the area. Our study also demonstrates that changes in anuran richness and beta diversity in the Cerrado can be driven by climatic predictors, mainly by climatic anomaly in temperature extremes and precipitation.

Changes in climate at the regional level can potentially result in either negative or positive consequences for the size and position of species distribution (Garcia et al., 2014b). Our study provides alarming information regarding species loss and restructuring of anuran communities in Cerrado, indicating a significant decrease in species diversity across most of the biome, along with a restructuration of anuran communities. This pattern of loss in anuran richness is congruent with other studies carried out in the Cerrado (Alves-Ferreira et al., 2022a; Vasconcelos et al., 2018). The restructuring of communities and the subsequent loss of species also threatens the structure and proper functioning of the ecosystem (Rogers and McCarty, 2000). Such changes have the potential to disrupt the dynamics of species competition and interaction within these ecosystems (Tylianakis et al., 2008). The loss of interactions and ecological functions performed by anurans can result in ecological imbalances, negatively affecting the stability and health of the ecosystem as a whole (Hopkins, 2007).

The southern Cerrado is known to be the region with the higher anuran species richness in the biome (Brandão et al., 2004). Despite the high anuran taxonomic diversity, this region shows the highest deforestation rates in the entire Cerrado (Strassburg et al., 2017) and the lower coverage by protected areas (Françoso et al., 2020). Therefore, in addition to the expected impact of climate change, this rich community still suffers from the highest rates of

deforestation. Species occupying higher-altitude regions are also expected to be more vulnerable to climate change due to projected shifts in suitable environmental conditions to ever increasing altitudes (Alves-Ferreira et al., 2022a, 2022b). This hampers the ability of species to disperse, since the impact becomes more pronounced as the altitude occupied by a species increases (e.g. mountain top species), leading to a reduction in available climatic area (Alves-Ferreira et al., 2022a; Nori et al., 2016).

Ecological traits such as dispersal capacity and niche breadth can contribute to the variation in community composition and can lead to turnover of species (Dobrovolski et al., 2012). The turnover component was prevalent across the majority of Cerrado, suggesting that part of the anuran communities will be replaced by different species in 2050. This may suggest that species with restricted distribution range may be replaced by species widely distributed (Lenoir and Svenning, 2015), as species with restricted distribution are more likely to have range contractions (Saupe et al., 2015). Moreover, generalist species tend to have a higher chance of finding suitable resources and establishing interactions in a new location (Garcia et al., 2014a). This could result in increasing community homogenization (Socolar et al., 2016).

Our results also indicate that faster precipitation changes and the increases in the anomaly in temperature extremes, lead to higher change in species composition in the future. Since amphibians tend to have a limited amplitude of their critical thermal tolerance, temperature extremes can lead to large effects on their thermal tolerance, reducing their thermal performance (Tewksbury et al., 2008). Furthermore, amphibians are ectotherms and exhibit life history traits influenced by the external environment, and their metabolism is strongly related to environmental temperatures (Feder and Burggren, 1992). Therefore, even slight increases in temperature can lead to greater changes in amphibians richness patterns. Furthermore, it is projected that future warming scenarios exacerbates the frequency and intensity of drought and water stress (Intergovernmental Panel On Climate Change (Ipcc), 2022), and particularly Cerrado is projected to become even hotter and drier in the future (Hofmann et al., 2021).

These niche models do not explicitly incorporate any population-level mechanism or population processes (e.g. biotic interactions, dispersal and adaptive potential to abiotic conditions). In particular, the adaptive potential (based on genetic adaptations, phenotypic plasticity and behavioral adjustments for physiological responses) of local populations is not considered and has been a less studied mechanism affecting species' responses to climatic change so far (Diniz-Filho et al., 2019). The effects of climate change on organisms also depend

on the abilities of species to cope with different challenges and their capacity for adaptation (Chevin et al., 2010). While climate change metrics can serve as proxies, the impacts do not act in isolation. They interact with other human-induced threats, such as human-dominated areas, which become obstacles to species dispersal and establishment, hindering their search for climatically suitable areas (Brook et al., 2008).

Our results reveal information about the loss of species and the restructuring of anuran communities in the Cerrado, indicating a significant reduction in species diversity across much of the biome. These findings highlight the urgency of establishing conservation strategies to mitigate the effects of climate change on vulnerable species and ecosystems in the Cerrado. It is crucial to highlight the potential impact of climate change on anuran diversity in this biome.

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FIGURES AND FIGURES CAPTIONS

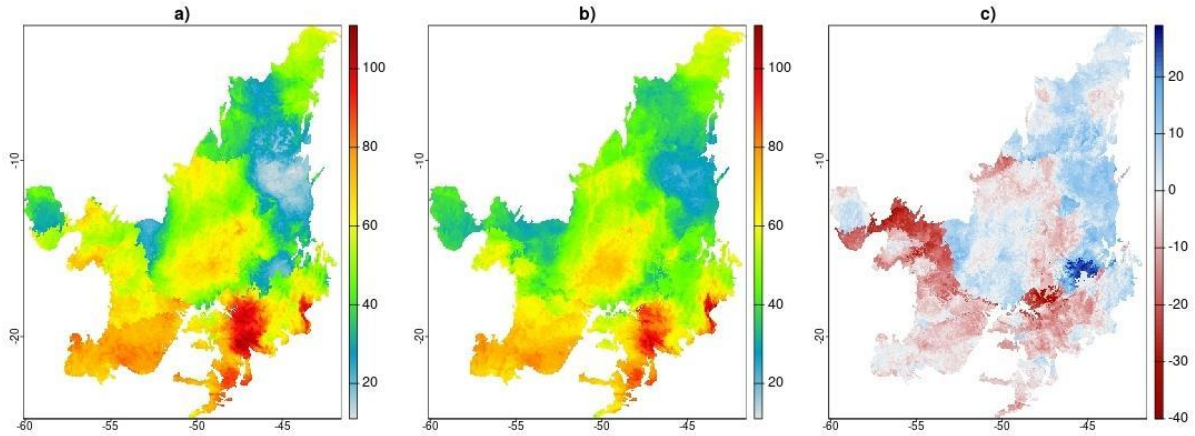

Figure 1. Spatial patterns of anurans species richness in the Brazilian Cerrado for (a) the current time (baseline), (b) pessimistic future climate scenarios (year 2050, SSP585), and (c) difference between the future and current richness (delta richness). In both the baseline and future scenarios (a and b), higher values (red color) correspond to elevated species richness, whereas lower values (blue color) correspond to low species richness. Positive values (blue color) in delta richness (c) indicate species gain, while negative values (red) indicate species loss.

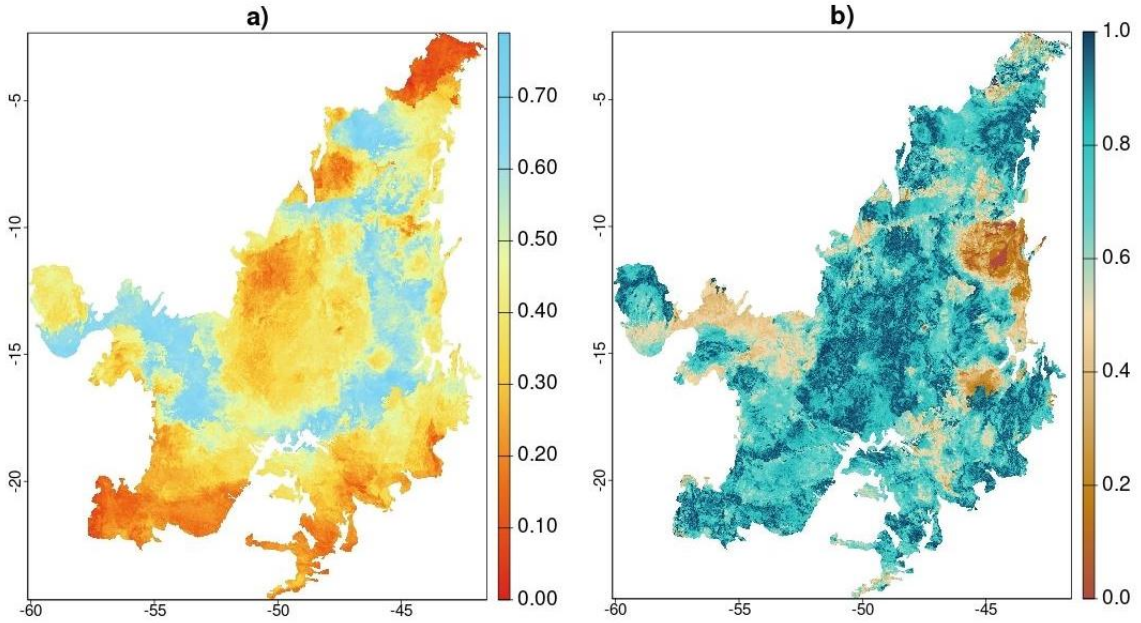

Figure 2. (a) Geographical distribution of the predicted temporal beta diversity of anurans in the Brazilian Cerrado calculated between the current baseline and future climate scenario. (b) Components of the anuran beta diversity: the proportion of replacement (turnover) predominance is represented by values close to one (blue color) and values close to zero indicate predominance of nestedness (brown color).

Table 1. Standardized regression coefficients from simultaneous autoregressive models (SAR) for beta total and delta richness of anurans considering the baseline and future scenarios.

Delta richness				
Predictors	**Estimate**	**Std. Error**	**z value**	**p value**
(Intercept)	49.2614	1.0065	48.9419	< 0.001
Precipitation Anomaly	49.8080	3.9722	12.5390	< 0.001
Tmax Anomaly	-7.8984	0.1879	-42.0290	< 0.001
Tmin Anomaly	-1.2979	0.2109	-6.1550	< 0.001
Precipitation Change velocity	-0.3852	0.1725	-2.2334	0.0255

Tmax Change velocity	-0.0310	0.0076	-4.0906	< 0.001
Tmin Change velocity	-0.0036	0.0076	-0.4745	0.6352
Annual Mean Temperature	-0.5907	0.0421	-14.0253	< 0.001
Annual Precipitation	0.0005	0.0003	1.3965	0.1626
Richness – Baseline	-0.4371	0.0036	-121.2912	< 0.001
Beta total				
Predictors	**Estimate**	**Std. Error**	**z value**	**p value**
(Intercept)	1.2690	0.0153	83.0772	< 0.001
Precipitation Anomaly	-1.0233	0.0595	-17.1853	< 0.001
Tmax Anomaly	0.1491	0.0028	52.5164	< 0.001
Tmin Anomaly	0.0426	0.0032	13.3460	< 0.001
Precipitation Change velocity	-0.0130	0.0027	-4.8489	< 0.001
Tmax Change velocity	-0.0001	0.0001	-0.5685	0.5697
Tmin Change velocity	-0.0004	0.0001	-3.7290	< 0.001
Annual Mean Temperature	-0.0364	0.0006	-56.5474	< 0.001
Annual Precipitation	0.0000	0.0000	-8.3474	< 0.001
Richness – Baseline	-0.0041	0.0001	-74.9200	< 0.001

CONCLUSÕES

Nosso estudo revela previsões preocupantes para o futuro das espécies de anuros no bioma Cerrado. A análise da diversidade alfa indica um declínio, especialmente nas regiões sudeste e sudoeste, com perdas de até 30 espécies em 2050, contrastando com ganhos nas regiões norte e nordeste. A análise da diversidade beta destaca mudanças substanciais na composição das comunidades de anuros, impulsionadas principalmente pela substituição de espécies em todo o bioma. Os preditores climáticos, como extremos de temperatura e anomalias de precipitação, desempenham um papel significativo na formação dessas mudanças. Nossas análises de regressão destacam o impacto negativo das anomalias de temperatura na riqueza de espécies e destacam a complexa relação entre o clima e a diversidade beta de anuros.

O aumento esperado nos extremos de temperatura e as condições mais quentes e secas projetadas para o Cerrado nos próximos 20-30 anos amplificam os impactos potenciais nos padrões de riqueza de anuros. Os resultados enfatizam a urgência de integrar medidas e estratégias de conservação abrangentes e adaptativas para enfrentar a iminente perda de diversidade de espécies de anuros no Cerrado devido às mudanças climáticas.