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ARTICLE

Modeling the potential distribution to present and future of the poorly known species *Xenohyla eugenioi* Caramaschi, 1998 (Anura: Hylidae) with findings about its distribution, natural history, and conservation

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Abstract. The distribution of amphibians is conditioned by historical factors and ecological drivers. Thus, Ecological Niche Models are important tools to provide information on the potential distribution of the species and determine where they will be requirements in future. Mainly, rare species or with restricted areas of occurrence, because this information are essential to understanding of their living area, microhabitat use, or natural history, serving as a basis for preservation actions. *Xenohyla eugenioi* is a poorly known species, restricted to transition areas of Caatinga and Atlantic Forest from Minas Gerais to Sergipe. This species exhibits little biological information available and few specimens housed in museums, which difficulty to plan conservation strategies. Here our aim was modeling the current and future distribution and discussing about conservation of *Xenohyla eugenioi*. We searched for occurrence records through literature and scientific collections data. For the future (2071-2100), we used ensemble models from three algorithms (CTA, GLM and ANN) to two shared socioeconomic pathways (SSP370 and SSP585 scenarios). This species has approximately 650 km in straight line between the extreme localities, occurring mainly in bromeliads near to water bodies. The Ensemble method indicates the most suitable areas of occurrence were over ecotonal range between Caatinga and Atlantic Forest and our projections have showed suitable conditions to highlands (up to 1.000 m). However, in the future, is expected total erosion of the *X. eugenioi* populations, due climatic changes, which reinforce the caution to conservation of this poorly known species and necessity of studies about its ecology, natural history and distribution. Moreover, we hope that this work can contribute to the discovery of new records, characterizing the narrower niche space than this species may actually inhabit.

Keywords. Anura; Climate change; Extinction; Ecological Niche Modeling; Species distribution model.

INTRODUCTION

Understanding the processes and mechanisms that influence species diversity patterns is a widely studied and discussed issue in macroecology (Ricklefs & Schluter, 1993). The distribution of species is conditioned by historical factors, such as the dynamics of geographical barriers (Hoo-

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rn & Wesselingh, 2011). Furthermore, ecological drivers such as the set of environmental conditions provide a favorable habitat for the establishment of species (Soberón, 2007). For example, studies about resources used by anurans have shown how the biotic (*e.g.,* calling sites and prey availability) and abiotic (*e.g.,* temperature and humidity) factors bias their occurrence (Bertoluci & Rodrigues, 2002; Xavier *et al.,* 2015; Neves *et al.,* 2020; Ceron *et al.,* 2022). Understanding the distribution patterns of species provides an assessment of the risks to which it is subjected and is an important tool for determining priority areas for conservation (Guisan *et al.,* 2013).

Around 25% of amphibian species do not have any records within protected areas worldwide (Nori *et al.,* 2015; Oliveira *et al.,* 2017). In addition, many species have an inaccurate distribution and/or contain huge areas not sampled (Bini *et al.,* 2006). These facts make it difficult to dimension the real distribution of species, especially for those rare or with restricted areas of occurrence (Pearson *et al.,* 2007). Moreover, endemic species generally exhibit restricted relationships to specific conditions (*e.g.,* climate and biotic interactions), and many of them are poorly known in relation to their living area, microhabitat use, or natural history (Neves *et al.,* 2018). Therefore, it is essential to study the distribution of these species to serve as a basis for preservation actions.

Ecological Niche Models (ENM) are important tools to provide information on the potential distribution of the species according to suitable environmental conditions used by them (Elith & Leathwick, 2009). Besides, the use of the current environmental information about ecological niches may determine models where the requirements of the species niche in the future may be satisfied (Wiens *et al.,* 2009) and predict range shifts under climate changes (Fordham *et al.,* 2012). Thus, the ENMs have been applied to promote better conservation strategies (*e.g.,* Araújo *et al.,* 2011; Chen *et al.,* 2017), mainly, for poorly known species (Pearson *et al.,* 2007; Siqueira *et al.,* 2009).

The genus *Xenohyla* Izecksohn 1998 harbors two allopatric species that inhabit different biomes and live in bromeliads (Caramaschi, 1998): *X. truncata* (Izecksohn, 1959) and *X. eugenioi* Caramaschi, 1998. *Xenohyla truncata* is a frugivorous species (Silva & Brito-Pereira, 2006) that occurs in seasonally dry forest areas of the Atlantic Forest in "Restingas" (Henriques *et al.,* 1986) of Rio de Janeiro state (Caramaschi, 1998), is classified as "Near Threatened" by the IUCN Red List of Threatened Species (Carvalho-e-Silva *et al.,* 2004) and "Vulnerable" by national list of Ministério do Meio Ambiente (Bastos *et al.,* 2023a). This species occurs in Protected Areas (PAs) such as Reserva Particular do Patrimônio Natural (RPPN), Área de Proteção Ambiental (APA), Parque Natural and Área Natural (Bastos *et al.,* 2023a). *Xenohyla eugenioi* is restricted to transition areas of Caatinga and Atlantic Forest called "Agreste", occurring from the extreme north of Minas Gerais to Sergipe. It is not known from any official PAs (Caramaschi, 1998; Silvano & Pimenta, 2004; Almeida *et al.,* 2015), being classified as "Data Deficient" by the IUCN Red List of Threatened Species (Silvano & Pimenta, 2004), and "Least Concern" by national list of Ministério do Meio Ambiente (Bastos *et al.,* 2023b).

There are only eight localities known to *X. eugenioi* with some wide gaps between them, which may represent a lack of sampling effort or the presence of geographical barriers. The biggest gap is between the municipality of Ipirá, in Bahia State, and the municipality of Pedra Mole, in Sergipe State (Almeida *et al.,* 2015), with approximately 280 kilometers of discontinuity. In addition, habitat loss due to agriculture and cattle raising are potential threats to populations of this species (Almeida *et al.,* 2015). There is little information available on biological data about the species (Caramaschi, 1998; Almeida *et al.,* 2015; Marciano-Jr. *et al.,* 2021), with few specimens housed in museums, which reflect the difficulty to plan conservation strategies for this species.

For this reason and to better understand the distribution of this species, this study aims: (1) to predict a current and future distribution to *X. eugenioi* using ENMs; and (2) to discuss the conservation and effectiveness of the PAs in cover the potential distribution of the species.

MATERIAL AND METHODS

Species occurrences

We used eight occurrence points of *Xenohyla eugenioi* to fit the models (Table 1). We used seven points available in the current bibliography (Caramaschi, 1998; Napoli & Brandão, 2004; Feio *et al.,* 2006; Almeida *et al.,* 2015; Orrico *et al.,* 2020) and one record from three spec-

Table 1. Known localities of *Xenohyla eugenioi* in "Agreste" region (Caatinga and Atlantic Forest transition area), Brazil, with respectively municipality and locality, state, latitude and longitude in decimal degrees, elevation above sea level and references of the records. States: Sergipe (SE), Bahia (BA), and Minas Gerais (MG).

Point id	Municipality (locality)	State	Latitude	Longitude	Elevation (m a.s.l.)	Reference
1	Pedra Mole (Fazenda Senhor do Bonfim)	SE	−10.6211	−37.7316	128	Almeida *et al.* (2015)
2	Ipirá	BA	−12.1500	−39.7333	328	Napoli & Brandão (2004)
3	Planaltino	BA	−13.1765	−40.2383	907	**ZUFRJ – This study**
4	Maracás (Fazenda Boca do Mato)	BA	−13.4166	−40.4166	964	Caramaschi (1998)
5	Boa Nova*	BA	−14.3755	−40.2083	723	Orrico *et al.* (2020)
6	Poções	BA	−14.5333	−40.3666	781	Caramaschi (1998)
7	Planalto Bahiano	BA	−14.6666	−40.4666	930	Caramaschi (1998)
8	Salto da Divisa (Santana, Ondina and Fazenda Jaboti)	MG	−16.0852	−40.0341	134	Feio *et al.* (2006)

* The coordinate shown is from centroid municipality's urban area sourced by us.

imens housed in the amphibian collection of Universidade Federal do Rio de Janeiro (ZUFRJ): ZUFRJ168486, ZUFRJ168487 and ZUFRJ168488.

Environmental data

We used bioclimatic variables to model the current and future geographic range of *X. eugenioi*. The climatic data were obtained from CHELSA v2 dataset (Karger *et al.,* 2017), which represents a set of 19 bioclimatic variables based on monthly precipitation and temperature values averaged between 1981-2010 (current time) and 2071-2100 (future time). We extracted bioclimatic layers at 30 arc-sec of spatial resolution and applied a variable selection procedure. More specifically, we passed the pairwise correlation matrix among the bioclimatic layers through a UPGMA clustering analysis to identify which climatic variables exhibit lower levels of multicollinearity (Dormann *et al.,* 2013). We ended up with five climatic variables, namely: Annual Mean Temperature (BIO01), Isothermality (BIO03), Temperature Seasonality (BIO04), Annual Precipitation (BIO12), and Precipitation Seasonality (BIO15). For future projections, we use the CMIP6 climatologies from three general circulation models (GCMs) (GFDL-ESM4, IPSL-CM6A-LR, and MRI-ESM2-0) provided by CHELSA. We selected these models due to their better ability to simulate temperature and precipitation variables we use (Firpo *et al.,* 2022).

For the future, we used two scenarios of shared socioeconomic pathways (SSP): the SSP370 scenario represents high challenges to mitigation and adaptation and SSP585 represents high challenges to mitigation and low challenges to adaptation (IPCC, 2022).

Species distribution models

For the elaboration of Ecological Niche Models (ENMs), we implemented Ensemble of Small Models (ESM, Lomba *et al.,* 2010; Breiner *et al.,* 2015) that is developed for rare species (Lomba *et al.,* 2010). The ESM strategy builds models with predictor subsets, and then, these subsets are evaluated according to a model performance metric obtained through cross-validation (see below). Finally, all subsetted models are averaged into a weighted ensemble model (Breiner *et al.,* 2018). We used three modelling algorithms in our ESM: artificial neural network (ANN, Manel *et al.,* 1999), generalized linear models (GLM, McCullagh & Nelder, 1989), and classification and regression tree (CTA, Breiman *et al.,* 1984). These algorithms were found to be best performing when using presence-only data (Breiner *et al.,* 2015, 2018). Pseudo-absences were randomly generated within the study area and matched the same number of real presences for *X. eugenioi*. We built the models and predictions 100 times for each algorithm, selecting each time a different 75% random sample of the true occurrences (Lomba *et al.,* 2010; Breiner *et al.,* 2015). Model accuracy was always verified against the remaining 25% using True Skill Statistics (TSS, Allouche *et al.,* 2006). TSS range from −1 to 1, where values above zero indicate a better than random prediction. All analyses were performed in R language (version 3.5.2, R Core Team, 2019) with raster, rgdal, and ncdf4 packages (Bivand *et al.,* 2023; Hijmans, 2023; Pierce, 2023).

We applied the minimal predicted area method (MPA, Engler *et al.,* 2004) to establish a threshold value to convert habitat suitability measures (varying between 0 and 1) into binary maps (0 = absence, 1 = presence). MPA predicts a potential area that is adequately small but still includes the maximum number of true species occurrences. To define the probability threshold, we extracted the value of habitat suitability for each observed occurrence in the current projection map and computed the value corresponding to the percentile 90%. Thereby, the binary distributions encompassed 90% of the real occurrences. After that, we overlap the potential area found in our models with the existent network of Protected Areas of the Brazilian Ministry of Environment and calculated the potential protected distribution of the species.

RESULTS

Extent of occurrence records

Xenohyla eugenioi is known from eight localities (Table 1) occurring near water bodies between the north of the Jequitinhonha River in Minas Gerais state and south Vaza-Barris River in Sergipe state, also taking place in the interior of the state of Bahia (Fig. 1). The records have approximately 650 km between the extreme localities in the south (municipality of Salto da Divisa) and in the north (municipality of Pedra Mole). This species is restricted to the northern Atlantic Forest and the region of its ecotone with the Caatinga and no record is found in Protected Areas, only in "Areas of Permanent Protection" (APPs) under Brazilian Federal Law 12,651/2012 (see below in discussion session; Toledo *et al.,* 2010).

Potential distribution and modeling

The TSS values for *X. eugenioi* were relatively high (mean ± SD = 0.9844 ± 0.023) indicating good model fits. TSS value for Ensemble model reached higher than the others algorithms (mean = ANN: 0.9957, CTA: 0.9493, GLM: 0.9961, and Ensemble: 0.9962) and thus the following results are based on the Ensemble models and their projections.

The Ensemble binarized projection (threshold = 917.85) indicates the most probable areas of occurrence were over an ecotonal range between Caatinga and Atlantic Forest which extends of the Minas Gerais to Pernambuco states through of extent area of approximately 6.005 km² (Fig. 1). Our Ensemble projection have shown suitable conditions for areas with high altitudes (up to 1.000 m), and the Central-South region of Bahia. Moreover, we found environmental suitability to Pernambuco state, the only region found above São Francisco River and far from any known record of *X. eugenioi* (Fig. 1).

Of the total potential area resulting from our models, about 480 km² (7.99%) are sheltered by some Protected Area (PA). These PAs that can house the species are Chapada Diamantina National Park (NP), Boa Nova NP, Alto do Cariri State Park (SP), Sete Passagens SP, Espelhado Municipal Natural Park (MNP), Macaqueiras MNP, Boa Nova Wildlife Refuge, Marimbus/Iraquara Environmental Protection Area, Serra do Orobó Area of Relevant Ecological Interest, Cachoeira do Ferro Doido Natural Monument, Arco Verde "private reserve" (RPPN), Riacho da Serra RPPN, Reserva Ganesha RPPN, Reserva Lendas do Caió RPPN, Reserva Casa do Sol RPPN, Reserva Serra do Luar RPPN, and Campos Novos RPPN.

For the future (2100), the projections showed large contractions in the suitable areas for the species (Fig. 2). Climatic suitability areas passed its range from 0-1 at present to 0-0.378 in both future scenarios (SSP370, and SSP585). Applying the threshold, there will not have environmental conditions for the survival of *X. eugenioi* according to all GCMs and in both scenario. Thus, it is expected the extinction of the species, due to dramatic climate changes.

DISCUSSION

We presented the first ecological and distribution study of *Xenohyla eugenioi* integrating literature data and specimens housed in museums to predict the potential distribution currently and in the future, beyond the extinction risk due to climate change. Here, our current projection for *X. eugenioi* suggests that environmental traits such as temperature and precipitation can explain the occurrence of the species in the ecotonal regions of the Atlantic Forest and Caatinga. Moreover, suitable areas for its occurrence must withdraw in the future (2100) and the species may become extinct as a consequence, according to all projections generated.

The Ensemble projection indicates the species has narrow distribution to ecotonal areas and highlands from branch of the National Park Chapada Diamantina in the

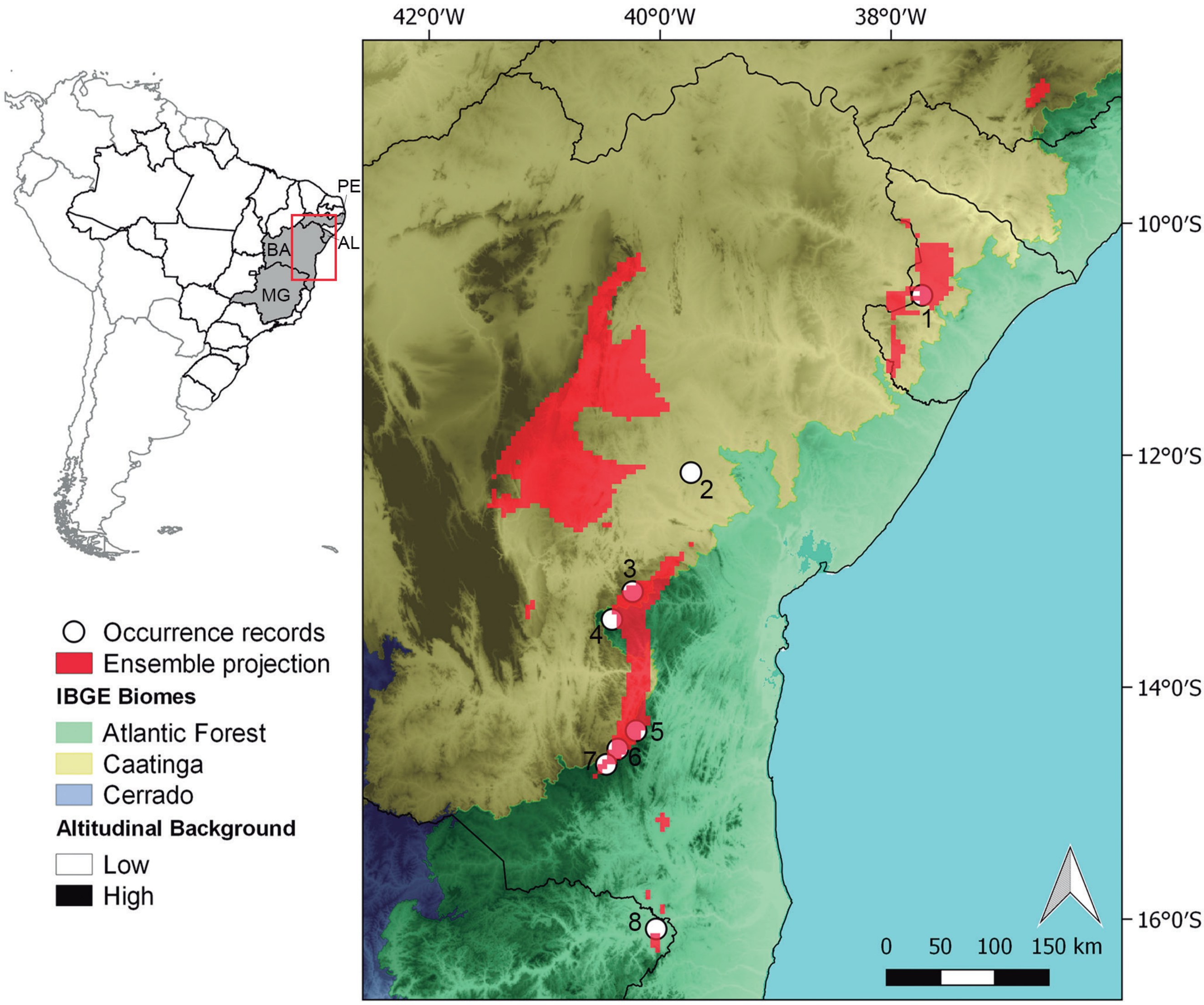

Figure 1. Geographic distribution of known records of *Xenohyla eugenioi,* and total extent area from Ensemble binarized projection (Potential distribution) (6.005 km²). The number of the records follow localities in Table 1. Inset map: South America with states: Pernambuco (PE), Bahia (BA), Alagoas (AL), and Minas Gerais (MG) states.

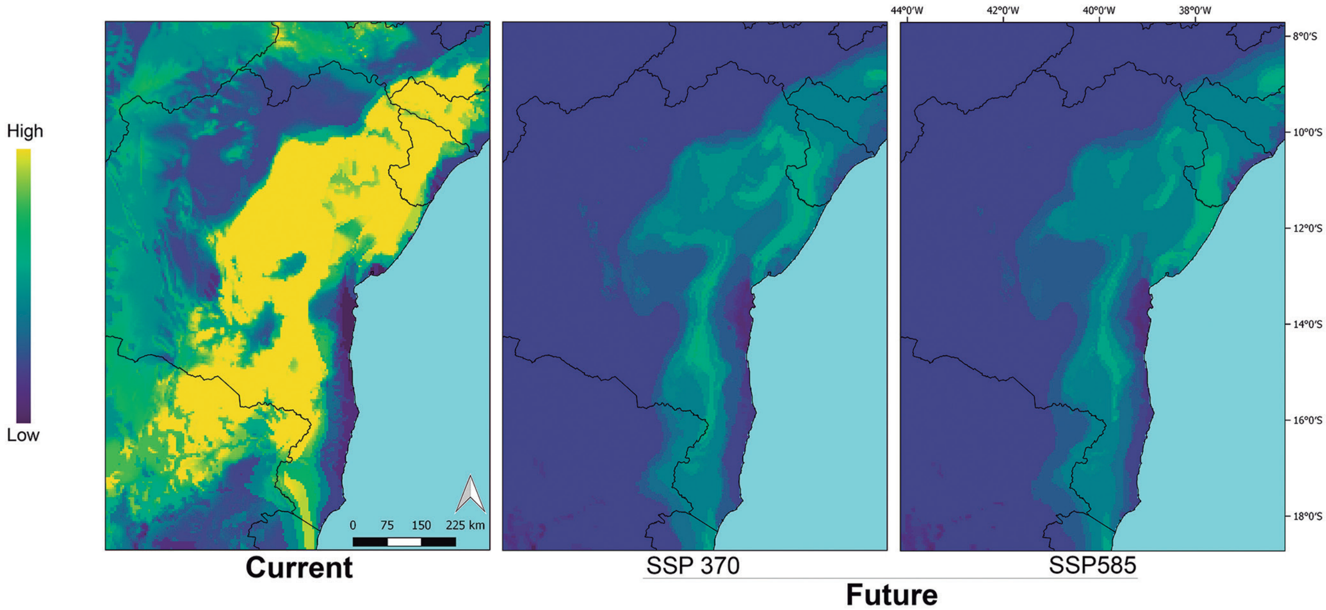

Figure 2. Ensemble suitability areas projections (range from 0 to 1) for *Xenohyla eugenioi* based on three climatic models and climate layers, considering an intermediate and high anthropogenic CO_2 emission (SSP370 and SSP585).

Central-South region of Bahia state (Figs. 1 and 2). The Chapada Diamantina, the northern part of Espinhaço Mountain Complex, is characterized by the occurrence of endemic taxa with a high diversity of anurans (Garda *et al.,* 2017; Guedes *et al.,* 2020). Thus, we believe to be possible the occurrence of *X. eugenioi* in this area, because its relationships with high altitudinal and ecotonal areas, as demonstrated through the true occurrence of the specimens (Table 1) and the result of our models (Fig. 1). Furthermore, we suggest expeditions with focal samples where the Ensemble projection shows high environmental susceptibility to its occurrence, which can enable new records and, consequently, more information about their populations and threats.

Nowadays, all records of *X. eugenioi* are found inside terrestrial bromeliads or perches in shrubs of up to 1.5 m height on edge of streams in areas of permanent protection (APPs) (Caramaschi, 1998; Almeida *et al.,* 2015; Marciano-Jr. *et al.,* 2021). Although approximately 8% of its potential distribution is within Protected Areas, this protection does not currently encompass any record. This information brings up the caution to species conservation because its occurrence is associated to areas with high anthropic pressure, due cattle raising and agriculture (Metzger, 2010; Almeida *et al.,* 2015). Mainly, because the populations of *X. eugenioi* found here (Fig. 1) are in regions with only 5% to 20% from original landscape (Ribeiro *et al.,* 2011).

In addition to the known impacts on the area of occurrence of the species, the future projections exhibited here did not recover suitable climatic areas for the species in 2100 for all GCMs used, increasing the pressure for the extinction of *X. eugenioi.* This result match closely to previous estimates indicating loss of climatically suitable areas to anurans from Atlantic Forest (Toledo *et al.,* 2010; Vasconcelos *et al.,* 2018). Thus, we consider fundamental the protection of the land and water over its distribution as suggested by Silvano & Pimenta (2014), mainly, due to the actual pressure of the habitat loss on their populations. Then, we suggest integrated strategies as maintenance of large conservation corridors and restoration of gallery forest (*see* Tabarelli *et al.,* 2005), which are action can guarantee connectivity among populations and quality of the environment (Toledo *et al.,* 2010).

Ecological research related to distribution, life history, ecological traits, population size, and trends are necessary to understand and assess the real threat situation of the species (Silvano & Pimenta, 2004). This way, the lack of information on biological aspects difficult the understanding of the ecological relationship between *X. eugenioi* and other species. While is well-documented *X. truncata* life cycle as a bromelicolous species (*sensu* Peixoto, 1995) that lives in the *Neoregelia cruenta* and reproduces in pounds nearby by indirect development (Izecksohn, 1998), the knowledge about *X. eugenioi* life cycle is still unclear. All literature and our records have found *X. eugenioi* in terrestrial bromeliads, but the lack of observation of reproduction and juvenile specimens prevents the recognition as a bromelicolous or bromeligenous species (*sensu* Peixoto, 1995). Fieldwork also made it possible to observe the presence of *X. eugenioi* in *N. cruenta* (BBC pers. obs.) and *Aechmea* sp. (Marciano-Jr. *et al.,* 2021), but it is still soon to confirm as a restriction like it is with *X. truncata* (Izecksohn, 1959, 1998). This possible strict relationship can reveal a coadaptation process, while understanding the life cycle may elucidate which factors are necessary to *X. eugenioi* lives in bromeliads. Thus, we hope future ecological questions of *X. eugenioi* can be measured and answered, which are important to species conservation and management.

Therefore, our study brings up the most complete locality points of *X. eugenioi* made so far, together with ecological niche modeling. Our models have shown the relationship of *X. eugenioi* to highlands and ecotonal areas, which in the future the climatic changes must withdraw suitable areas to its occurrence causing its extinction. Moreover, these data reinforce the caution to the conservation of this poorly known species and present an alert to requirement studies about its ecology, natural history and distribution. We hope that this work will contribute to the discovery of new records, characterizing the narrower niche space than the species may actually inhabit.

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