University of Kent

Kent Academic Repository

Barata, Izabela M., Uhlig, Vivian M., Cortês, Lara G., Fath, Franciele and Griffiths, Richard A. (2024) *Overcoming the lack of distribution data for range-restricted habitat specialist frogs.* Austral Ecology, 49 (5). ISSN 1442-9985.

Downloaded from

https://kar.kent.ac.uk/106000/ The University of Kent's Academic Repository KAR

The version of record is available from

https://doi.org/10.1111/aec.13522

This document version

Author's Accepted Manuscript

DOI for this version

Licence for this version

UNSPECIFIED

Additional information

Versions of research works

Versions of Record

If this version is the version of record, it is the same as the published version available on the publisher's web site. Cite as the published version.

Author Accepted Manuscripts

If this document is identified as the Author Accepted Manuscript it is the version after peer review but before type setting, copy editing or publisher branding. Cite as Surname, Initial. (Year) 'Title of article'. To be published in ***Title of Journal*** , Volume and issue numbers [peer-reviewed accepted version]. Available at: DOI or URL (Accessed: date).

Enquiries

If you have questions about this document contact ResearchSupport@kent.ac.uk. Please include the URL of the record in KAR. If you believe that your, or a third party's rights have been compromised through this document please see our Take Down policy (available from https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies).

Overcoming the lack of distribution data for range-restricted habitat specialist frogs

Izabela M. Barata [1,2*], Vivian M. Uhlig [3], Lara G. Cortês [3], Franciele Fath [3], and Richard A. Griffiths [4]

[1] Durrell Wildlife Conservation Trust, Les Augrès Manor, Trinity, Jersey, JE3 5BP, Channel Islands

[2] Instituto Biotrópicos, Diamantina, Minas Gerais, Brasil

[3] Centro Nacional de Pesquisa e Conservação de Répteis e Anfíbios, Instituto Chico Mendes de Conservação da Biodiversidade, Goiânia, Goiás, Brasil

[4] Durrell Institute of Conservation and Ecology, School of Anthropology and Conservation, University of Kent, Canterbury, Kent, United Kingdom

[*] Corresponding author: izabela.barata@durrell.org

Abstract: With over 40% of species threatened with extinction, the distributional range of most amphibians is still unknown, generating uncertainty whether species are naturally rare, under-sampled or difficult to detect. We implemented a modelling approach that uses bromeliads as surrogates to predict the distribution of habitat specialist frogs that lack distributional data. We aimed to predict and survey potential new sites for occurrence of a rare and microendemic bromeliad-dwelling frog from the Atlantic Rainforest of Brazil. We used Maxent to predict suitable areas based on climate and topographic profiles, combined with 21 occurrence records of bromeliads within which our target frog species (*Crossodactylodes itambe*) is strictly restricted. The bromeliad-based models identified four areas potentially suitable and subsequent surveys revealed an entirely new species of a rare bromeliad-dwelling frog in one of the areas. We demonstrate that using easy-to-survey surrogate species that have a strong relationship with species that are hard to detect has enormous potential to reveal crucial information on potential ranges and distribution of cryptic taxa. Such surrogate modelling approach could be extended to other habitat specialist species that lack distribution data such as amphibians restricted to specific refugia and/or reproduction sites. This could improve the targeting of surveys and increase understanding of the patterns of rarity and the drivers of species distribution, especially for areas with high endemicity and range-restricted frogs.

Keywords: bromeligenous frogs, distribution models, few occurrence data, Maxent, new species, rare species.

1. INTRODUCTION

Most range-restricted species are rare, concentrated in tropical areas and threatened with extinction (Pimm & Jenkins, 2010; Morais et al., 2012). These species are of high conservation concern, but the absence of reliable distribution data means there is uncertainty concerning their conservation status (Mace et al., 2008). A quarter of amphibians in the world have very small geographical ranges (<10^3 km^2) (Pimm et al., 2014) and 41% of species are at risk of extinction (Luedtke et al., 2023) with the great majority living in the tropics (Stuart et al., 2008). Equally, amphibians are often habitat specialists and have reduced dispersal capabilities. Bromeliad-dwelling frogs are a case in point. Out of 99 species of bromeligenous frogs, 35% are either data deficient or not evaluated, and 41% are threatened with extinction (Sabagh et al., 2017). Restricted to South America, bromeligenous frogs are known from very few locations and spend their entire life cycle within bromeliads. In extreme cases, these frogs are restricted to a single species of plant, with one known population recorded at a high-elevation site that can be challenging to survey (MacCulloch & Lathrop, 2005; Barata et al., 2013; Kok et al., 2013).

Understanding how range-restricted species are distributed and where new populations are likely to be found can indicate whether these species are indeed naturally rare or simply under-sampled. Species distribution modelling (SDM) can be used to identify under-sampled locations to prioritize surveys of range-restricted species (Raxworthy et al., 2003) – an approach that has been sucessfully applied across different geographic regions and taxa (Pearson et al., 2007; Marini et al., 2010; Chunco et al., 2013; Sarkinen et al., 2013; McCune, 2016). However, the substantial lack of information in tropical areas (Collen et al., 2008) hampers futher application of the method which relies on species occurrence records. When there are limited data on the target species, SDMs can be generated by using information from a species that is more abundant yet associated with a rare species. In such cases, a strong association and similar habitat requirements between a lesser common species and the targeted rare species can be beneficial (Edwards et al., 2005). With very limited distribution data available, bromeligenous frogs are challenging for modelling, however, their unique life history traits create an exceptional opportunity for modelling species distribution. We used bromeliads as surrogates for frog occurrence, and even though there was little information on the target frog species, we produced models using occurrence records of bromeliads that are more widely available.

We built SDMs using bromeliad distribution data to predict new potential areas for a range-restricted habitat specialist, the Itambe's bromeliad frog (*Crossodactylodes itambe*). The species extent of occurrence is less than 0.5 km^2 in a single location at 1700 m a.s.l., in the Atlantic Rainforest of Brazil (Barata et al., 2013). Species is Critically Endangered under the criteria of geographic range, quality of habitat and population number (IUCN/SSC/ASG, 2023a; Barata et al., 2018a). To understand species distribution and investigate its patterns of rarity, we aimed to a) predict and map areas of high suitability for plants and describe environmental requirements for plant occurrence; and b) search for new populations of the target frog in areas of high suitability located inside and outside protected areas. As such, our results focused not only on the geographical extent of bromeligenous frogs and their levels of threat, but also to the general implications of survey effort of montane endemic species and habitat specialist amphibians in tropical areas. We demonstrate that the success of our modelling approach can lead to promising applications of SDM to endemic habitat specialist species allowing us to understand patterns of rarity of many elusive frogs for which we have no data and that are otherwise difficult to survey.

2. METHODS

2.1 Study system and modelling approach

Tank bromeliads are large arboreal or terrestrial plants with a central tank that collects water, leaf litter and detritus, providing a wide range of microhabitats for numerous species (Lehtinen, 2004). Bromeligenous frogs are strictly dependent on bromeliads, where they lay their eggs and complete their life cycle without leaving the plant (Peixoto, 1995). Half of these 99 bromeligenous frogs are restricited to montante areas higher than 1000 m a.s.l. (Sabagh et al., 2017), and their ecology and natural history are poorly known. The genus *Crossodactylodes* comprises seven small-sized bromeligenous frogs which are range restricted, rare and occur in specific species of bromeliads in montane areas of the Atlantic Forest of Brazil. Our target species, *Crossodactylodes itambe*, is known to occur on one mountaintop in the Espinhaço Mountain Range of Brazil (Barata et al., 2013) – a 1200 km biodiversity-rich mountain chain that divides the Atlantic Rainforest to the east, and the Cerrado to the west. *Crossodactylodes itambe* lives in a single species of tank bromeliad, *Vriesea medusa* (Santos et al., 2017), which is also endemic to two locations in the Espinhaço Range (Versieux et al., 2008; Versieux et al., 2010). Despite the cryptic nature of all *Crossodactylodes* spp., there is information available on the taxonomy (Barata et al., 2013; Santos et al., 2020), reproduction (Santos et al., 2017; Santos et al., 2021), behaviour (Barata et al., 2018b) and ecology (Barata et al., 2017; Barata et al., 2018a) of our targeted species *C. itambe*, serving as a good candidate to investigate species distribution base on habitat requirements.

In Maxent, model outcome can be strongly affected by the background points chosen (Elith et al. 2010). Our goal was to identify areas where our targeted species could potentially occur, in the vicinities of current known extent of occurrence. We therefore restricted the geographical scale of our models to the southern portion of the Espinhaço Range – a UNESCO Biosphere Reserve that also comprises a mosaic of protected areas of different sizes and shapes (hereafter, Espinhaço Mosaic). Since *C. itambe* is a small-sized frog with limited dispersal capabilities, drawing background points from a smaller scale enabled projections to be made without extrapolating to areas outside the likely range of our targeted species. Hence, our goal was to predict suitable areas for bromeliads and ground-truth likely areas for new populations of *C. itambe* within the limits of the Biosphere Reserve and the Espinhaço Mosaic (Figure 1A). Since *C. itambe* is known from a single site, we used bromeliads as a surrogate for species presence and we therefore modelled not our target species, but the environmental requirements for occurrence of bromeliads. *Vriesea* is one of the most diverse genera of bromeliads in our study area (Versieux & Wendt, 2006) and contains some of the largest species. Considering that the structure of the bromeliad such as size, number of leaves, volume of the central tank and number of neighbouring plants are important predictors of abundance for *C. itambe* (Barata et al., 2018a), at least five other species of *Vriesea*, with similar size and structure (i.e., larger plants with larger water tanks), were used to generate our models. We therefore used occurrence records of the genus *Vriesea*, assuming the structure of the plant – rather than plant species – would be important for frog occurrence.

2.2 Occurrence and environmental data

To obtain occurrence records of the bromeliads, we searched for *Vriesea* species in nine locations between 1029 m - 1592 m a.s.l. within our study area. We selected these locations using Google Earth images at 100 m resolution, by comparing images with similar outcrops where bromeliads can potentially occur. We used the method validated by Silva & Alves-Silva (2013) and identified similar areas based on vegetation cover and substrate type, comparing the surrounding landscape with the Itambé summit, where *C. itambe* originally occurs. Although we acknowledge this method might introduce some bias by sampling similar outcrops, we aimed at maximising the number of records that could be used in our models.

In 2015, we surveyed these areas gathering occurrence records of *Vriesea* spp. Over 6-days we had a total of 133 occurrences recorded in GPS, but these records were, inevitably, very close to each other (on some occasions <100 m), which could increase the chances of model overfitting by including records that are not spatially independent (Shcheglovitova & Anderson, 2013). Therefore, we only used records of bromeliads that were at least 1 km apart from each other. We filtered these records with ArcGIS version 10.5.1, creating a 1 km buffer around every occurrence, and identifying overlapping occurrences that were later excluded. Consequently, we had a total of 21 unique records that could be used in our distribution models (Figure 1B).

For environmental data we downloaded 19 bioclimatic variables and altitude from WorldClim Global Climate Data version 2 (Fick & Hijmans, 2017; at 30 seconds resolution, ~1 km^2), and soil type (1:650.000) from the Department of Soils and AgroSciences at the Federal University of Viçosa, in Brazil (available at https://dps.ufv.br/softwares/). Elevation is an important factor for the occupancy and abundance of *C. itambe* (Barata et al., 2017; Barata et al., 2018a). Additionally, the bromeliads we modelled have rupicolous life form, growing on rocky fields characterized by shallow and sandy soils (Versieux and Wendt, 2006).

Using ArcGIS, we standardized all environmental variables, using the same extent and cell size, and defined their geographical boundaries accordingly to the study area. We built distribution models by combining climatic variables, altitude, and soil type. We selected climatic variables by performing a Principal Component Analysis (PCA) in ArcGIS and selecting variables that contributed most to the first and second axes of principal components and that were not correlated according to the correlation matrix output from the PCA (values <0.5). Outputs from PCA provide the variance explained by Eigenvector coefficients (indicating the relative weight of each variable in the component), percentage Eigenvalues and accumulative Eigenvalues, which we interpreted as the contribution of each axis as the principal components of our analysis (see Supplementary Information for details).

2.3 Model settings and validation

We used Maxent version 3.4.1 (Phillips et al., 2006) to identify suitable areas based on climate and topographic profiles, combined with 21 (presence-only) occurrence records of at least five species of bromeliads from the genus *Vriesea*. Small sample sizes may compromise the power of predictions (Stockwell & Peterson, 2002) but Maxent performs well compared to other algorithms (Elith et al., 2006; Wisz et al., 2008), even with sample sizes below 20 records (Hernández et al., 2006; Papeş & Gaubert, 2007; Pearson et al., 2007; Williams et al., 2009; Le Lay et al., 2010; Marini et al., 2010; Chunco et al., 2013). We built 12 different models with Maxent using slightly different settings (details available as Supplementary Information). For all models we created response curves and predictions using a Jackknife to measure variable importance, with a logistic output, and set the number of maximum iterations to 5000. The area under the receive-operator curve (AUC) is usually used to evaluate models, however, AUC values should be used with caution for presence only methods (Merow et al., 2013). To test the predictive performance of our models we used a Jackknife approach described by Pearson et al. (2007), which is reliable for small sample sizes. The test compares success-failure for each model to the proportion of the study area predicted present i.e., performance is assessed based on the ability of each model to predict the single locality excluded from the training data in the leave-one-out procedure (Pearson et al., 2007). A P-value was calculated based on the predictions of our models (R script available at http://www.ucl.ac.uk/cber/pearson).

Although we fitted 12 models for parametrisation using different Maxent settings (details available as Supplementary Information), here we present a final model that contained a layer of soil type, altitude, and the selected climatic variables. For this final model, we modified Maxent settings following recommendations for small samples: we applied a Jackknife cross-validation (or leave-one-out procedure, Peason et al., 2007), using the minimum training presence threshold, regularization multiplier of 2 and a hinge feature (Shcheglovitova & Anderson, 2013; Radosavljevic & Anderson, 2014).

Finally, to validate our final model we surveyed areas indicated in our projections. Areas were selected based on a combination of high suitability for bromeliad occurrence and low standard deviations (≤0.05) predicted in the models, the predictive performance of models (given by the Jackknife approach), and we also considered expert knowledge (I. M. Barata, personal observation). We selected areas both inside and outside protected areas (PA) to compare differences in plant numbers and plant structure (i.e., tank size). We assumed that areas inside PA were well preserved and more likely to contain good quality habitat, whereas areas outside PA were presumed to be impacted by human activities, such as fire and cattle grazing. We collected data on bromeliad tank size (height and width of central tank, in centimetres) and total number of bromeliads recorded. We performed a t-test to evaluate significant differences on tank size of bromeliads inside and outside PA. If bromeliads were verified during daytime surveys they were resurveyed after dusk to search for *C. itambe*. Each area was intensively surveyed during 2-4 consecutive days during the rainy season, between January and March 2017.

3. RESULTS

3.1 Predicting environmental suitability for plant occurrence

Fitted models identified similar areas of high suitability, showing consistency in predictions across different settings (Supplementary Information). The model presented here (with selected bioclimatic variables, altitude and soil type) gave us broader predictions but also higher *SD* when compared to other models, expanding predictions to the south of study area (Figure 2). Projections in the north-east were consistent across all models, which falls within the limits of the Atlantic Rainforest. Results from Jackknife showed a high and significant success rate for our model ($r = 0.9$, $P < 0.05$). Low *SD* were associated with areas to the east, especially when compared to areas on the south where predictions were less precise (Figure 2).

Overall, suitable areas for bromeliad occurrence are high elevational sites with appropriate soil type (i.e., outcrop with shallow soil and quartz gravels, low in nutrient content), with reduced seasonal variation in temperature (response curves and output summaries available in Supplementary Information). Temperature seasonality was an important variable for bromeliad occurrence with reduced tolerance in seasonality, daily fluctuations, and extreme conditions. Temperature seasonality and annual precipitation explained 97% of variation according to the

PCA (and were therefore the selected as climatic variables for modelling, details available in Supplementary Information). While temperature seasonality represents change over the year and had a negative influence in our predictions, annual precipitation is the sum of all monthly rainfall and can be used to interpret the importance of water availability to a species distribution – in our case it was positive for the bromeliad. Nonetheless, the selected climatic variables (temperature seasonality and annual precipitation) contributed to less than 15% of predicted area and projections were mostly influenced by altitude and soil type.

3.2 Searching for new populations of frogs

Bromeliads were present in every area predicted by the models that we surveyed. Areas to the east not only had a high predicted suitability with lower *SD* but are also under the domains of the Atlantic Rainforest, which is the same biome where original population of *C. itambe* is currently recorded. We therefore opted to survey areas within the domains of the Atlantic Rainforest and located in the north-east of our study area (Figure 2). Due to financial and logistic constraints (limited manpower, reduced time, and poor road access), we selected four different areas to be surveyed, two inside PA (12,184 ha and 13,6541 ha) and two outside PA. These areas are on average 38.4 km from each other and located within the Espinhaço Mosaic, which covers an area of approximately two million hectares.

We recorded a total of 541 bromeliads. The areas differed in the total number of bromeliads available (inside PA = 462, outside PA = 79) and elevational range (varying from 1029 m to 1592 m a.s.l.). Bromeliad had larger tanks inside PAs (mean = 79 cm^2, *SD* = 36.1, *N* = 112) than outside PAs (mean = 37.9 cm^2, *SD* = 13.1, *N* = 55; $P < 0.005$, t-value = 10.7, *df* = 155). Although every recorded bromeliad was resurveyed during the night, we only found frogs in one of the four predicted areas: a forested patch inside a PA (Figure 3), about 60 km from the original population. Further examination of sampled individuals in the lab revealed that our new record was not a new population of *C. itambe*, but in fact a new species of the genus *Crossodactylodes* (recently described by Santos et al., 2023). This PA has high altitude (1519–1620 m a.s.l.) and falls completely within the domains of the Atlantic Rainforest (Figure 3). Different from other areas we surveyed, the forest patch where frogs were found contained a high density of plants and the PA had bromeliads with the largest tanks (mean = 88.6 cm^2; *SD* = 42.5; *N* = 63).

4. DISCUSSION

We generated distribution models for a widely distributed genus of bromeliad to predict the occurrence of a habitat specialist amphibian for which data are limited, prioritising survey areas highly suitable for plants where our target plant-dependent species was, consequentially, more likely to be found. Our modelling approach is suitable for species that have a strong dependency on their host plant but for which there is otherwise limited information on determinants of distribution (and therefore no other parameter can be modelled). The method could be broadly extended to range-restricted habitat specialist species that require further investigation on their extent of occurrence, such as other threatened and data deficient bromeligenous frogs (c.75% of species, Sabagh et al., 2017) and other amphibians species that are presumed to occur more widely and are constrained to specific refugia and/or breeding sites, such as tree buttresses, waterfilled tree holes, bamboo stumps, nut husks, leaf axils, and other such habitats.

Overall, our models yielded consistent predictions despite the use of a small dataset, compensating for the lack of data on our target species. Valuable occurrence data for bromeliads could also be obtained from open access digital herbariums (Besnarda et al., 2018; Heberling et al., 2019). For instance, we found over 3000 records from the last 10 years of *Vriesea* species available on the Global Biodiversity Information Facility, contrasting with the poor data on *Crossodactylodes* species distribution, demonstrating the potential of digital databases in contributing to modelling plant-dependent species. When fieldwork is needed, obtaining presence data for plants can be less time consuming and more cost effective than searching for the targeted animal species. For example, to collect bromeliad occurrence, we covered an extensive area in six days of survey, resulting in more than 130 records. On the other hand, at least four nocturnal visits are needed to reliably detect our target frog (Barata et al., 2017), requiring greater logistical and financial support. Modelling bromeliad data, collected either in the field or from online databases, is therefore a feasible and cost-effective alternative approach for other species in the genus. At least four *Crossodactylodes* species are expected to occur more widely, one of which is threatened with extinction with decreasing population (VU *Crossodactylodes izeckshoni* IUCN/SSC/ASG, 2023b) and other that has not been recorded since its first collection in 1909 (DD *C. pintoi* IUCN/SSC/ASG, 2023c), and further intensive surveys should be conducted to define species extent of occurrence, habitat restrictions and patterns of rarity. This is also a good opportunity for developing a true test of the performance of the suggested modelling approach by comparing the occurrence of bromeliads and frogs between sites with both high and low suitability, according to the models.

Noteworthy, bromeliads can determine the distributional ranges of plant-dependent animals under the assumption that their environmental and climatic requirements will encompass those of the target species. Our results give further support that our target species is indeed restricted to high altitude, possibly occupying bromeliads that tolerate environments with low temperature variation and higher water availability. Consequently, these strict environmental conditions for plant distribution might also restrict species range resulting in species being microendemic and having low tolerance to habitat disturbance. Furthermore, the abundance of bromeligenous frogs can be highly dependent on the bromeliad structure and the presence of water in bromeliad tanks (Barata et al., 2018a). Frogs were only recorded inside PA and our results shed light on the impacts of environmental change on the occurrence of habitat specialist amphibians. Although we recorded bromeliads in every area we visited, they varied in number, quality, and size. Outside PA the number of plants was lower, and size of bromeliad was significantly reduced. In these locations, we observed that the structure of plants was damaged, either by fire and or cattle trampling. Considering the high rate of deforestation recorded in the Atlantic Rainforest of Brazil (Ribeiro et al., 2009), it is more likely that discoveries of new populations (or even new species) will fall inside areas where potential threats are expected to be reduced, such as remote locations and PA that held more pristine habitats.

Finally, our results reinforce the need for additional survey effort, especially in tropical areas that remain insufficiently represented in amphibian conservation studies (Ficetola, 2015). Species with restricted ranges might be naturally rare or suffer from insufficient survey effort but distinguishing between these two can be difficult. Ecological observations are uneven throughout South America (Martin et al., 2012) where all bromeligenous frogs are known to occur, and in

Brazil survey effort is unequally distributed (Oliveira et al., 2016), including in our study area (Barata, Correia and Ferreira, 2016). The discovery of a new species demonstrates that montane regions still need increased sampling effort to uncover their full biodiversity. Despite our survey effort we only found frogs in one new area, indicating that both targeted and newly discovered species are naturally rare with a genuinely restricted distribution. This might be true for many other range-restricted taxa that are constrained to high altitudes and depend on bromeliads thriving on specific environmental and climatic conditions. We conclude that the use of surrogates for habitat specialist species can enhance the potential of SDM, allowing a wise allocation of survey effort to substantially improve our knowledge on the distribution of rare and range-retricted amphibians that are currently under threat. Additional case-studies will improve our understanding on the geographical extent of poorly known amphibian species, however, such pattern of rarity (with restricted habitat requirements and small distributional range) is likely true for other bromeligenous frogs.

Acknowledgements

We are grateful to Rufford Small Grants and The Mohammed bin Zayed Species Conservation Fund for funding field work. ICMBio provided license (22361-1). IMB was supported by PhD scholarship from CAPES Foundation (BEX 13153-13-7). We thank park managers Silvia Duarte from Itambé State Park, Paula Leão from Sempre-Vivas National Park, Tonhão de Almeida from Rio Preto State Park, and Wanderlei Lopes from Serra Negra State Park, for their logistical support during expeditions. We are grateful to Aílton Ferreira and Michel Becheleni, for volunteering during frog surveys, and Guilherme Ferreira for defining accessibility to sampled locations and for assistance during expeditions and night surveys.

Conflict of interest

The authors declare no conflicts of interest.

Author contribution statement

IMB and RAG contributed to study concept and design. Fieldwork and data collection was delivered by IMB. Data analysis was done by IMB with input from VMU and LGC and FF produced the maps. IMB led on the writing of the article with equal contributions from each of the other authors.

Supplementary Information

Details of different settings and predictive maps for 12 models built using Maxent is available online, including plotted standard deviation and bioclimatic variables used in the final model discussed in this manuscript. A summary table of explanatory variables, Principal Components Analysis results and response curves and output summary for models’ performance from Maxent are also available online.

References

Barata, I. M., Santos, M. T., Leite, F. S., & Garcia, P. C. (2013) A new species of *Crossodactylodes* (Anura: Leptodactylidae) from Minas Gerais, Brazil: First record of genus within the Espinhaço Mountain Range. Zootaxa 3731, 552–56.

Barata, I. M., Griffiths, R. A., & Ridout, M. S. (2017) The power of monitoring: optimizing survey designs to detect occupancy changes in a rare amphibian population. Sci Rep 7:1–9.

Barata, I. M., Silva, E.P., & Griffiths, R. A. (2018a) Predictors of abundance of a rare bromeliad-dwelling frog (*Crossodactylodes itambe*) in the Espinhaço Mountain Range of Brazil. J Herpetol 52:321–326.

Barata, I. M., Griffiths, R. A., & Ferreira, G. B. (2018b) Activity pattern and behavior of an endemic bromeliad frog observed through camera trapping. Herpetological Review 49(3):432–438.Besnard, G., Gaudeul, M., Lavergne, S., Muller, S., Rouhan, G., Sukhorukov, A. P., Vanderpoorten, A., & Jabbour, F. (2018) Herbarium-based science in the twenty-first century. Botany Letters 165:323–327.

Collen, B., Ram, M., Zamin, T., & McRae, L. (2008) The tropical biodiversity data gap: addressing disparity in global monitoring. Trop Conserv Sci 1:75–88.

Chunco, A. J., Somphouthone, P., Niane, S., & Bryan, L. S. (2013) Predicting environmental suitability for a rare and threatened species (Lao Newt, *Laotriton laoensis*) using validated species distribution models. PLoS ONE 8:e59853.

Edwards Jr, T. C., Cutler, D. R., Zimmermann, N. E., Geiser, L., & Alegria, J. (2005) Model-based stratifications for enhancing the detection of rare ecological events. Ecology 86:1081–1090.

Elith, J., Graham, C. H., Anderson, R. P., Dudík, M., Ferrier, S., Guisan, A., Hijmans, R. J., Huettmann, F., Leathwick, J. R., Lehmann, A., & Li, J. (2006) Novel methods improve prediction of species' distributions from occurrence data. Ecography 29:129–151.

Elith, J., Kearney, M., & Phillips, S. (2010) The art of modelling range-shifting species. Methods in Ecology and Evolution 1: 330–342.

Ficetola, G. F. (2015) Habitat conservation research for amphibians: methodological improvements and thematic shifts. Biodivers Conserv 24:1293–1310.

Fick, S. E., & Hijmans, R. J. (2017) Worldclim 2: New 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology.

Heberling, J. M., Prather, L. A., & Tonsor, S. J. (2019) The changing uses of herbarium data in an era of global change: an overview using automated content analysis. BioScience 69:812–822.

Hernández, P. A., Graham, C. H., Master, L. L., & Albert, D. L. (2006) The effect of sample size and species characteristics on performance of different species distribution modeling methods. Ecography 29:773–785.

IUCN SSC Amphibian Specialist Group & Instituto Boitatá de Etnobiologia e Conservação da Fauna (2023a) *Crossodactylodes itambe*. The IUCN Red List of Threatened Species 2023: e.T78458984A86254644. Accessed on 19 February 2024.

IUCN SSC Amphibian Specialist Group & Instituto Boitatá de Etnobiologia e Conservação da Fauna (2023b) *Crossodactylodes izeckshoni*. The IUCN Red List of Threatened Species 2023: e.T78458984A86254644. Accessed on 19 February 2024.

IUCN SSC Amphibian Specialist Group & Instituto Boitatá de Etnobiologia e Conservação da Fauna (2023c) *Crossodactylodes pintoi*. The IUCN Red List of Threatened Species 2023: e.T78458984A86254644. Accessed on 19 February 2024.

Kok, P. J. R., Willaert, B., & Means, D. B. (2013) A new diagnosis and description of *Anomaloglossus roraima* (La Marca, 1998) (Anura: Aromobatidae: Anomaloglossinae), with description of its tadpole and call. S Am J Herpetol 8:29–45.

Le Lay, G., Engler, R., Franc, E., & Guisan, A. (2010) Prospective sampling based on model ensembles improves the detection of rare species. Ecography 33:1015–1027.

Lehtinen, R. (2004) Ecology and evolution of phytotelm-breeding anurans. Miscellaneous Publications of the University of Michigan.

Luedtke, J. A., et al. (2023) Ongoing declines for the world's amphibians in the face of emerging threats. Nature 622(7982):308–314.

MacCulloch, R. D., & Lathrop, A. (2005) Hylid frogs from Mount Ayanganna, Guyana: New species, redescriptions, and distributional records. Phyllomedusa 4:17–37.

Mace, G. M., Collar, N. J., Gaston, K. J., Hilton-Taylor, C. R., Akçakaya, H. R., Leader-Williams, N. I., Milner-Gulland, E. J., & Stuart, S. N. (2008) Quantification of extinction risk : IUCN’s system for classifying threatened species. Conserv Biol 22:1424–1442.

Marini, M. A., Barbet-Massin, M., Lopes, L. E., & Jiguet, F. (2010) Predicting the occurrence of rare Brazilian birds with species distribution models. J Ornithol 151:857–866.

McCune, J. L. (2016) Species distribution models predict rare species occurrences despite significant effects of landscape context. J Appl Ecol 53:1871–1879.

Merow, C., Smith, M. J., & Silander Jr, J. A. (2013) A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter. Ecography 36(10): 1058–1069.

Morais, A. R., Braga, R. T., Bastos, R. P., & Brito, D. (2012) A comparative analysis of global, national, and state red lists for threatened amphibians in Brazil. Biodivers Conserv 21:2633–2640.

Oliveira, U., Paglia, A. P., Brescovit, A. D. et al. (2016). The strong influence of collection bias on biodiversity knowledge shortfalls of B razilian terrestrial biodiversity. Divers Distrib 22:1232–1244.

Papeş, M., & Gaubert, P. (2007). Modelling ecological niches from low numbers of occurrences: Assessment of the conservation status of poorly known viverrids (Mammalia, Carnivora) across two continents. Divers Distrib 13:890–902.

Pearson, R. G., Raxworthy, C. J., Nakamura, M., & Townsend Peterson, A. (2007) Predicting species distributions from small numbers of occurrence records: A test case using cryptic geckos in Madagascar. J Biogeog 34:102–117.

Peixoto, L. O. (1995) Associação de anuros a bromeliaceas na Mata Atlântica. Revista Universidade Rural, Série Ciências da Vida 17:75–83.

Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006) Maximum entropy modeling of species geographic distributions. Ecol Model 190:231–259.

Pimm, S. L., Jenkins, C. N., Abell, R., Brooks, T. M., Gittleman, J. L., Joppa, L. N., Raven, P. H., Roberts, C. M., & Sexton, J. O. (2014) The biodiversity of species and their rates of extinction, distribution, and protection. Science 344:6187.

Pimm, S. L., & Jenkins, C. N. (2010) Extinctions and the practice of preventing them. In: Sodhi NS, Ehrlich PR. (eds) Conservation Biology for All. Oxford University Press, pp. 181–198.

Radosavljevic, A., & Anderson, R. P. (2014) Making better Maxent models of species distributions: Complexity, overfitting and evaluation. J Biogeog 41:629–643.

Raxworthy, C. J., Martinez-Meyer, E., Horning, N., Nussbaum, R. A., Schneider, G. E., Ortega-Huerta, M. A., & Peterson, A. T. (2003) Predicting distributions of known and unknown reptile species in Madagascar. Nature 426:837–841.

Ribeiro, M. C., Metzger, J. P., Martensen, A. C., Ponzoni, F. J., & Hirota, M. M. (2009) The Brazilian Atlantic Forest: How much is left, and how is the remaining forest distributed? Implications for conservation. Biol Conserv 142:1141–1153.

Sabagh, L. T., Ferreira, R. B., & Rocha, C. F. D. (2017) Host bromeliads and their associated frog species: Further considerations on the importance of species interactions for conservation. Symbiosis 73:201–211.

Santos, M. T. T., Pezzuti, T. L., Barata, I. M., Leite, F. S., & Garcia, P. C. (2017) The tadpole of the microendemic, bromeligenous *Crossodactylodes itambe* (Anura, Leptodactylidae) from the endangered "campo rupestre" of Southeastern Brazil, with additional comments on natural history. S Am J Herpetol 12:14–23.

Santos, M. T. T., Magalhães, R. F., Ferreira, R. B., Vittorazzi, S. E., Dias, I. R., Leite, F. S., Lourenço, L. B., Santos, F. R., Haddad, C. F., & Garcia, P. C. (2020). Systematic Revision of the Rare Bromeligenous Genus *Crossodactylodes* (Anura: Leptodactylidae: Paratelmatobiinae). Herpetological Monographs 34(1):1–38.

Santos, M. T. T., Barata, I. M., Ferreira, R. B., Haddad, C. F., Gridi-Papp, M., & de Carvalho, T.R. (2022) Complex acoustic signals in *Crossodactylodes* (Leptodactylidae, Paratelmatobiinae): a frog genus historically regarded as voiceless. Bioacoustics 31(2):175–190.

Santos, M. T., Pinheiro, P. D., Garcia, P. C., Griffiths, R. A., Haddad, C. F., & Barata, I. M. (2023) A New Species of *Crossodactylodes* from the Espinhaço Mountain Range, Southeastern Brazil (Anura: Leptodactylidae: Paratelmatobiinae). Herpetologica 79(2):108–118.

Sarkinen, T., Gonzáles, P., & Knapp, S. (2013) Distribution models and species discovery: the story of a new Solanum species from the Peruvian Andes. PhytoKeys 31:1.

Shcheglovitova, M., & Anderson, R. P. (2013) Estimating optimal complexity for ecological niche models: A jackknife approach for species with small sample sizes. Ecol Model 269:9–17.

Silva, H. R., & Alves-Silva, R. (2013) Predictive-like distribution mapping using Google Earth: Reassessment of the distribution of the bromeligenous frog, *Scinax v-signatus* (Anura: Hylidae). Zootaxa 3609:213–22.

Stockwell, D. R. B., & Peterson, A. T. (2002) Effects of sample size on accuracy of species distribution models. Ecol Model 148:1–13.

Stuart, S. N., Hoffman, M., Chanson, J. S., Cox, N. A., Berridge, R. J., Ramani, P., & Young, B. E. (eds) (2008) Threatened amphibians of the world. Lynx Editions, IUCN and Conservation International, Barcelona.

Versieux, L. M., & Wendt, T. T. (2006) Checklist of Bromeliaceae of Minas Gerais, Brazil, with notes on taxonomy and endemism. Selbyana 27:107–146.

Versieux, L. M. (2008) Checklist and one new species of Bromeliaceae from Pico do Itambe, Minas Gerais, Brazil. Bot J Linn Soc 158:709–715.

Versieux, L. M., Louzada, R. B., Viana, P. L., Mota, N., & Wanderley, M. G. L. (2010) An illustrated checklist of Bromeliaceae from Parque Estadual do Rio Preto, Minas Gerais, Brazil, with notes on phytogeography and one new species of *Cryptanthus*. Phytotaxa 10:1–16.

Williams, J. N., Seo, C., Thorne, J., Nelson, J. K., Erwin, S., O'Brien, J. M., & Schwartz, M. W. (2009) Using species distribution models to predict new occurrences for rare plants. Divers Distrib 15:565–576.

Wisz, M. S., Hijmans, R. J., Li, J., Peterson, A. T., Graham, C. H., Guisan, A., & NCEAS Predicting Species Distributions Working Group (2008) Effects of sample size on the performance of species distribution models. Divers Distrib 14:763–773.

Figure captions

Figure 1. Study area with (A) the location of the Biosphere Reserve and the Espinhaço Mosaic (blue area) in the state of Minas Gerais, in south-eastern Brazil; and (B) filtered occurrence records (triangles, N = 21) of the bromeliad *Vriesea* spp. used in our models. Star shows the known population of our target species *Crossodactylodes itambe*.

Figure 2. Suitable areas predicted for bromeliad occurrence and associated standard deviations (*SD*) from customised model. Value represents habitat suitability on a scale from 1 to 0 (on prediction) and standard deviations on a scale of 0 to 0.05 (on *SD*). Prediction warm/darker colours indicating high suitability and *SD* warm/darker colours indicates high standard deviation. Dashed circles indicate areas with both high suitability and low *SD*.

Figure 3. Areas of high suitability based on the reduced model and the original occurrence of *Crossodactylodes itambe*, showing the four visited locations. Detailed map shows the limits of the Cerrado (CE) and the Atlantic Rainforest (AF) with bromeliad records and the occurrence of the new *Crossodactylodes* species.

Figures

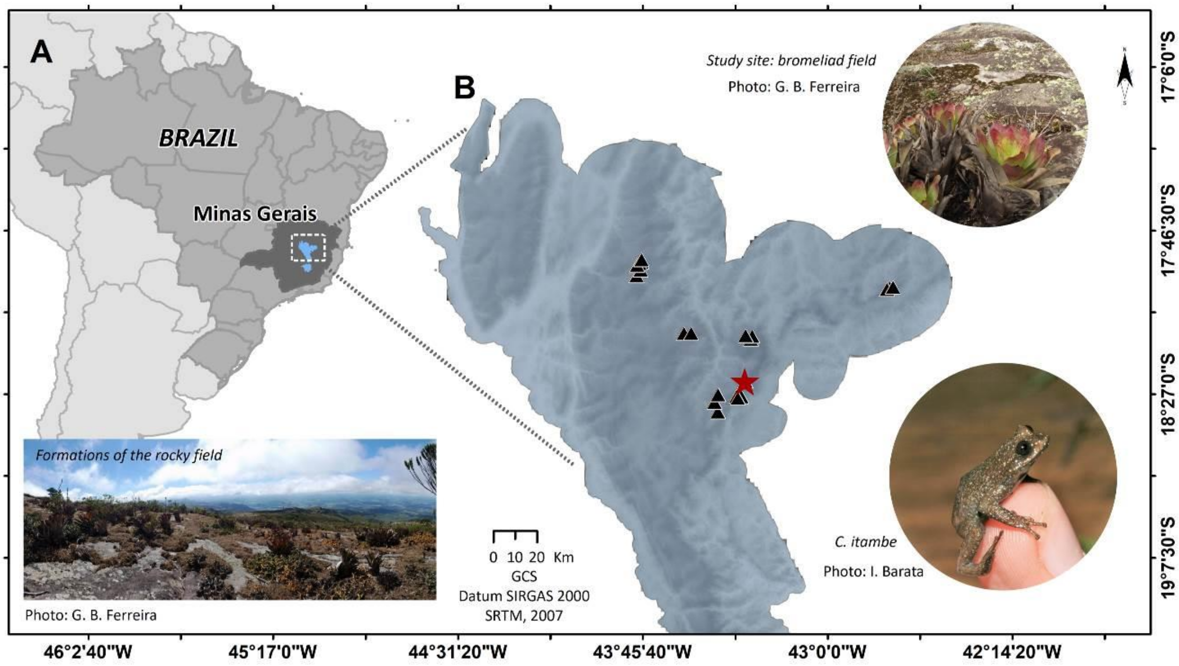

Figure 1. Study area with (A) the location of the Biosphere Reserve and the Espinhaço Mosaic (blue area) in the state of Minas Gerais, in south-eastern Brazil; and (B) filtered occurrence records (triangles, N = 21) of the bromeliad *Vriesea* spp. used in our models. Star shows the known population of our target species *Crossodactylodes itambe*.

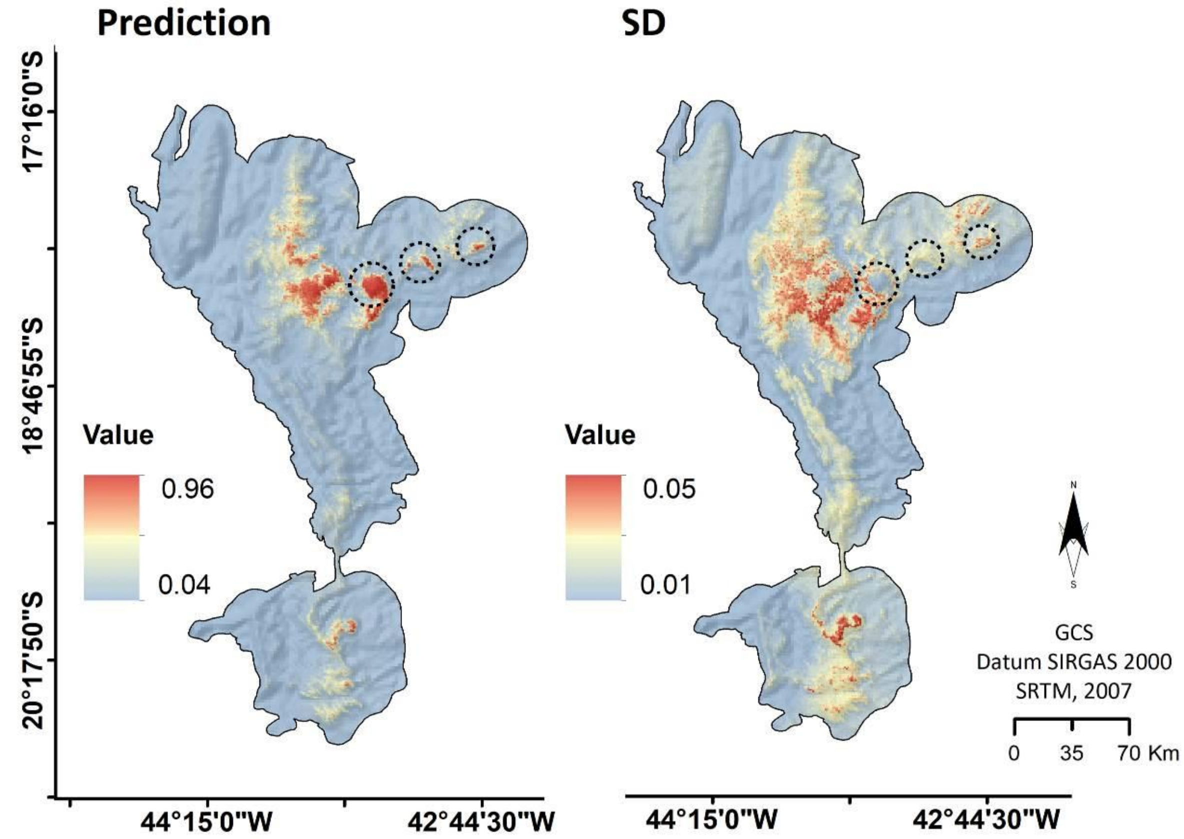

Figure 2. Suitable areas predicted for bromeliad occurrence and associated standard deviations (*SD*) from the customised model. Value represents habitat suitability on a scale from 1 to 0 (on prediction) and standard deviations on a scale of 0 to 0.05 (on *SD*). Prediction warm/darker colours indicating high suitability and *SD* warm/darker colours indicates high standard deviation. Dashed circles indicate areas with both high suitability and low *SD*.

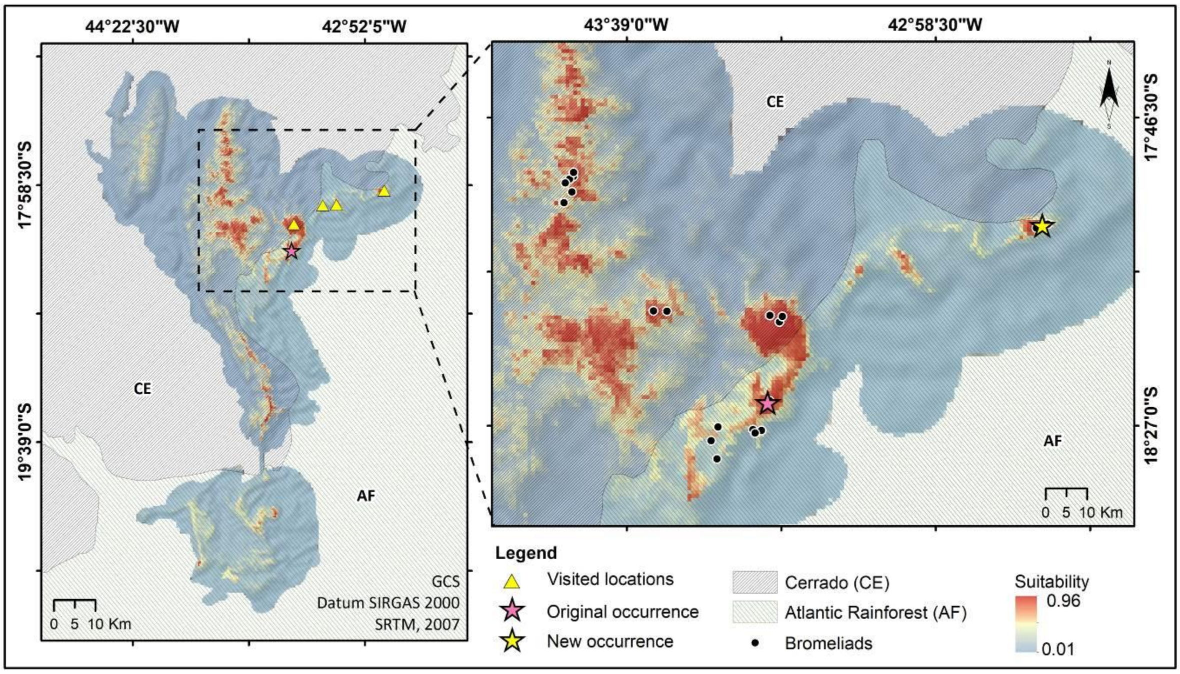

Figure 3. Areas of high suitability based on reduced model and the original occurrence of *Crossodactylodes itambe*, showing the four visited locations. Detailed map shows the limits of the Cerrado (CE) and the Atlantic Rainforest (AF) with bromeliads records and the occurrence of the new *Crossodactylodes* species.