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Article

Predicting potential distribution and evaluating biotic interactions of threatened species: a case study of *Discocactus ferricola* (Cactaceae)

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Abstract: Information on distribution, number of populations, and biotic interactions are essential for assessing the threat status of species and to establish more effective conservation initiatives. Ecological niche modeling have been successfully applied to identify the potential distribution, even for rare species that have few recorded occurrence points. In this study, we evaluated the potential distribution and additionally generated the first data on the reproductive biology of *Discocactus ferricola*, due to its degree of threat and the absence of ecological data for that species. The potential distribution map highlighted areas with higher probability of occurrence of *D. ferricola* on the Residual Plateau of Maciço do Urucum located in Mato Grosso do Sul, Brazil. The occurrence of *D. ferricola* populations was limited to outcrops of flat ironstone (cangas) distributed in patches across the landscape, increasing the chances of serious threats, such as habitat loss due to mining and species extraction. We also found that *D. ferricola* is xenogamous. Therefore, *in situ* conservation actions must prioritize the maintenance of interactions with pollinators by preserving the flora and fauna of rocky outcrops and adjacent forests in areas of greater environmental suitability for *D. ferricola*. Our study highlights the use of ecological niche modeling and data on biotic interactions to evaluate species potential distribution, to guide new sampling efforts, and to assist conservation and management initiatives.
Keywords: *Conservation; ecological niche modeling; pollinator dependence; outcrop; restrict distribution.*

Prevendo a distribuição potencial e avaliando interações bióticas de espécies ameaçadas: um estudo de caso de *Discocactus ferricola* (Cactaceae)

Resumo: Informações sobre distribuição, número de populações e interações bióticas são essenciais para avaliar o status de ameaça das espécies e estabelecer iniciativas de conservação mais eficazes. A modelagem de nicho ecológico tem sido aplicada com sucesso para identificar a distribuição potencial, mesmo para espécies raras que possuem poucos pontos de ocorrência registrados. Neste estudo, avaliamos a distribuição potencial e adicionalmente geramos os primeiros dados sobre a biologia reprodutiva de *Discocactus ferricola*, devido ao seu grau de ameaça e à ausência de dados ecológicos para essa espécie. O mapa de distribuição potencial destacou áreas com maior probabilidade de ocorrência de *D. ferricola* no Planalto Residual do Maciço do Urucum localizado em Mato Grosso do Sul, Brasil. A ocorrência de populações de *D. ferricola* foi limitada aos afloramentos ferruginosos planos (cangas) que são distribuídos em manchas pela paisagem, aumentando as chances de ameaças graves, como perda de habitat devido à mineração e extração da espécie. Também descobrimos que *D. ferricola* é xenogâmica. Portanto, ações de conservação *in situ* devem priorizar a manutenção das interações com os polinizadores através da preservação da flora e da fauna nos afloramentos rochosos e florestas adjacentes nas áreas de maior adequabilidade ambiental para *D. ferricola*. Nesse estudo, nós destacamos o uso da modelagem de nicho ecológico e de dados sobre interações bióticas para avaliar a distribuição potencial de espécies, orientar novos esforços de amostragem e auxiliar iniciativas de conservação e manejo.
Palavras-chave: *afloramentos rochosos; conservação; dependência de polinizador; distribuição restrita; modelagem de nicho ecológico.*

Introduction

The occurrence points of a species carry information about its distribution, which is a complex expression of its ecology and evolutionary history (Brown 1995). Each point reflects part of realized niche and, therefore, contains information on abiotic conditions, biotic interactions, and the dispersion capacity that are required for the occurrence of species (Soberón & Peterson 2005). Thus, the points of occurrence can be used to construct ecological niche models (ENM) also known as species distribution models (SDM) (Soberón & Peterson 2005, Peterson et al. 2011, Peterson & Soberón 2012). This approach is considered of low cost and has been applied to several researches, especially for the conservation of species and biomes (Le Lay et al. 2010, Werneck et al. 2012, Sobral-Souza et al. 2018, Adhikari et al. 2019, Kolanowska & Jakubska-Busse 2020). Specifically, ENM has been used to identify likely areas for invasive species (Qiao et al. 2017, Zhu et al. 2017), in paleoecological studies (Lima-Ribeiro & Diniz-Filho 2013), to highlight areas of potential distribution (McCune 2016, Fois et al. 2018), to indicate areas for species reintroduction (Martínez-Meyer et al. 2006), among others.

Noteworthy, ecological niche modeling have been successfully applied to provide information on potential distribution of species even with few recorded occurrence points (Le Lay et al. 2010, McCune 2016, Fois et al. 2018). Distribution data is important for the assessment of the threat status of these species, since the extent of occurrence and number of populations are criteria used to define threat categories of the International Union for Conservation of Nature (IUCN) (Martinelli & Moraes 2013). After identifying the threat level, the next step is to implement *in situ* and or *ex situ* management actions, when necessary. For the correct management of species, information about their ecology, including reproductive aspects and biotic interactions, are required (Scheele et al. 2018). The lack of these information weaken management and conservation strategies, prevent adequate actions for population growth, and obscure the construction of more assertive hypotheses about the evolution and dispersion of species.

Basic information on distribution and reproductive biology are crucial for assessments of the current threat status of species and for the establishment of more accurate conservation plans, especially for rare and endangered species such as *Discocactus ferricola* Buining & Brederoo (Machado 2004, Ribeiro-Silva et al. 2011). This species is currently categorized as endangered on the Red List of Threatened Species of IUCN, mainly due to its small area of occurrence and small number of known populations (Braun 2013). In this study, we used the ecological niche modeling approach to assess the potential distribution and additionally to generate the first ecological data on reproductive biology of *D. ferricola*. The general aim of this study was to provide ecological data of *D. ferricola* to assist in conservation initiatives and to guide new sampling efforts. Specifically, we aimed to answer the following questions: (1) What is the current potential distribution of *D. ferricola*? (2) Does *D. ferricola* depend on pollinators for reproduction? (3) What species visit *D. ferricola* flowers?

Material and Methods

1. *Study area*

The present study was carried out on eight farms, a settlement and a municipal park, all located in the mountainous complex of the Residual Plateau of Maciço do Urucum (RPMU), in the municipalities of Corumbá and Ladário in Mato Grosso do Sul state, MS, Brazil (Tab. 1). According to Köppen's classification, the climate of the region is Aw megathermal, with dry winters and rainy summers (Soriano 2000). The average annual temperature is 25.1°C, with maximum temperatures reaching 40°C and minimum temperatures close to 0°C (Soriano 2000). The average annual precipitation is 1070 mm, and the average annual relative humidity is 75% (Soriano 2000).

2. *Studied species*

Discocactus ferricola has a flattened globular shape with a pale to dark green stem measuring 8-9 cm high and 20-25 cm in diameter (Anderson 2001). The number of ribs is 14, and they form tubercles (Anderson 2001). The 5-8 spines, arranged radially, are 4.5-5 cm and brown, becoming gray with age. The central spines are mostly absent but may present as one spine at 2-2.5 cm (Anderson 2001). The cephalium measures 7 cm high and 6.5 cm in diameter and has white wool with dark gray bristles that can be 5 cm (Anderson 2001). The flowers are white and tubular and measure 5.5 cm long (Figure 1A). The fruits are elongate to club shaped, measure 3-4 cm long, and are greenish cream to white. Seeds are broadly oval to subglobose and are shiny black color, with numerous papillae or tubercles, and they measure 2-2.5 mm long (Anderson 2001).

Discocactus ferricola is endemic to the mountainous complex of the RPMU on the border of Brazil and Bolivia (Braun 2013, Takahasi & Meirelles 2014). The RPMU is known as the oldest rock formation in the world, with intact exposed rocks that are approximately 70 million years old (Vasconcelos et al. 2019). In the RPMU, *D. ferricola* occurs on flat ironstone outcrops, locally known as "bancadas lateríticas" or "cangas", formed by the deposition of iron and manganese laterites in the drainage areas of the hills and slopes (Braun 2013, Takahasi & Meirelles 2014). *Discocactus ferricola* have clonal reproduction and is abundant locally, forming large aggregates (Figure 1B).

Currently, the main threats to *D. ferricola* are habitat loss due to mining (especially in Bolivia), human occupation, and species extraction, as this species is consumed as food, used as herbal medicine by traditional communities, and has ornamental potential (Lüthy 2001, Ribeiro-Silva et al. 2011, Braun 2013). The total area of occurrence of *D. ferricola* is approximately 20 km² patchily distributed on three outcrops of iron ore and manganese surrounded by Cerrado vegetation and forests (Braun 2013). Such habitats are threatened by mining and urbanization, which has led to a 30% population decline of *D. ferricola* over the last 30 years (Braun 2013). The continuous loss of adult individuals, its occurrence out of protected areas, and its generation time of 10 years also justify the endangered status of *D. ferricola* (Braun 2013).

3. *Species distribution modeling*

To identify areas of greatest climatic suitability for *D. ferricola*, we initially performed a search on the Global Biodiversity Information Facility (GBIF) and Species Link platforms to access all recorded occurrences. In addition, we actively searched for *D. ferricola* populations in the RPMU. The occurrence points were used to construct *D. ferricola* occurrence map. After removing uncertain, redundant, and historical data, we had 11 occurrence points of *D. ferricola* covering the entire known distribution of the species (Tab. 1). To remove environmentally autocorrelated points, a rarefaction analysis for environmental heterogeneity was carried out in ArcGIS v.10.3 (Anderson & Gonzalez 2011, ESRI 2014, Varela et al. 2014). The remaining 10 occurrence points were used to model the potential niche of the species (Tab. 1). The area included in the model extended approximately 140000 km^2 and contained the main rock outcrops of the region: 1- Rincon del Tigre in Bolivia, 2 - Serra do Amolar, 3 - Residual Plateau of Maciço do Urucum, and 4 - Serra da Bodoquena in Brazil.

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Table 1. Occurrence sites of *Discocactus ferricola* on the Residual Plateau of Maciço do Urucum, Mato Grosso do Sul state, Brazil.

Population	Latitude	Longitude	Origin	City
Vale do Paraíso	19° 10' S	57° 33' W	GBIF	Ladário
Estrada Parque Pantanal	19° 05' S	57° 36' W	Species Link	Ladário
Monjolinho	19° 16' S	57° 31' W	new record	Corumbá
Parque Piraputangas I	19° 14' S	57° 38' W	new record	Corumbá
Parque Piraputangas II	19° 17' S	57° 37' W	new record	Corumbá
São João	19° 10' S	57° 32' W	new record	Ladário
Mutum	19° 12' S	57° 51' W	new record	Corumbá
Carandá	19° 06' S	57° 31' W	new record	Ladário
Banda Alta	19° 09' S	57° 34' W	new record	Ladário
Rabichão	19° 09' S	57° 31' W	new record	Ladário

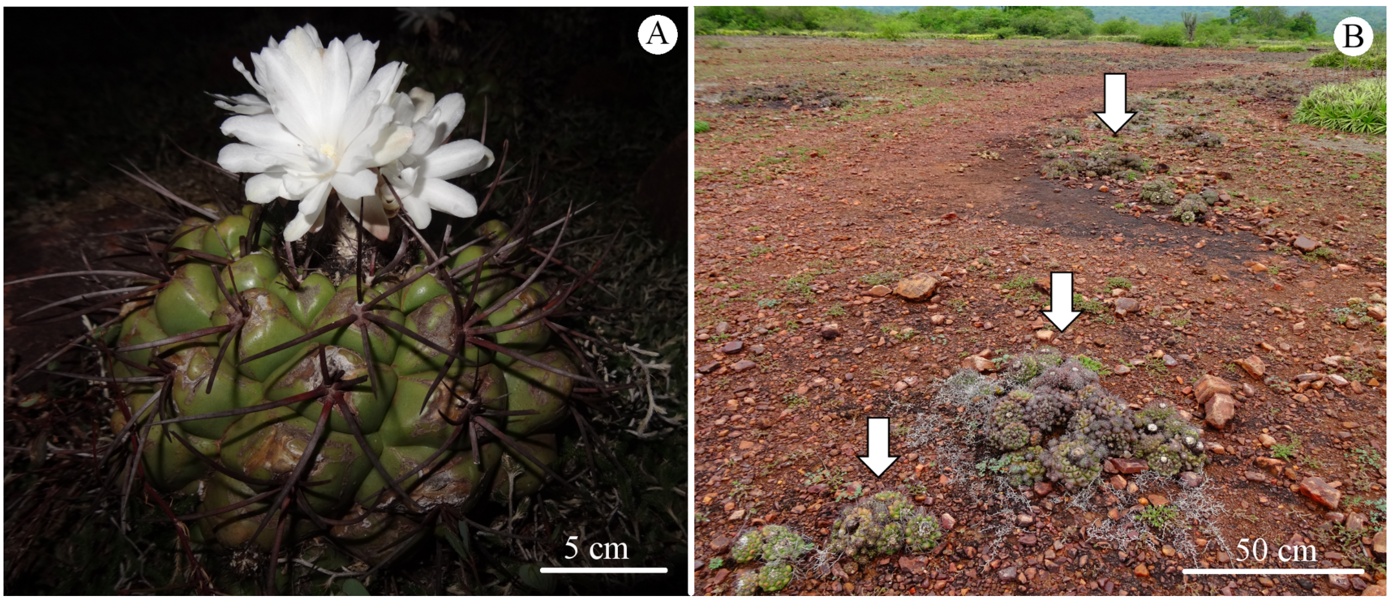

Figure 1. *Discocactus ferricola*. **A.** A closer look at one individual with opened nocturnal flowers. **B.** Flat ironstone outcrop area on the Vale do Paraíso farm showing the locally abundant population of *D. ferricola.* The arrows show aggregate individuals forming large clumps. The reddish color of the soil is typical of ironstone outcrops.

We used bioclimatic variables from the WorldClim database at a resolution of 30 arc sec (~1 km^2) (www.worldclim.org, Fick & Hijmans 2017) and the maximum entropy algorithm (MaxEnt v.3.4.1, Phillips et al. 2006) to model the potential niche distribution of *D. ferricola*. We used the area under the curve (AUC) receiver operating characteristics (ROC) to validate the output model from MaxEnt. We then used the maximum threshold value to produce a binary map and True Skill Statistics to evaluate its reliability (Allouche et al. 2006). Thus, we generated a final map that narrowed the searches for new populations in areas where *D. ferricola* would most likely occur. Four variables were used in the modeling: mean diurnal range (BIO2, mean monthly temperature (max temp - min temp)), mean temperature of the warmest quarter (BIO10), annual precipitation (BIO12), and precipitation of driest quarter (BIO17). The four variables were selected after a principal axis factor analysis with varimax rotation in a data set consisting of 19 bioclimatic variables, an elevation raster available from the database USGS (hydrosheds.cr.usgs.gov), and the Harmonized World Soil raster (www.fao.org, Fischer et al. 2008). We conducted analyses in R v.3.5.2 (R Core Team 2018) using the packages "vegan" (Oksanen et al. 2018), "raster" (Hijmans 2018), and "rgdal" (Nenzén & Araújo 2011, Porfirio et al. 2014, Bivand et al. 2018).

4. *Pollinator dependence*

We conducted four treatments on 46 flowers from 25 individuals to determine if *D. ferricola* depends on a pollinator for reproduction: (1) unmanipulated self-pollination (*n* = nine flowers) - the intact flower buds were bagged, and there was no additional manipulation; (2) manual self-pollination (*n* = 10 flowers) - intact flower buds were bagged, and as soon as the flowers opened, they were manually pollinated with their own pollen; (3) manual cross-pollination (*n* = 13 flowers) - intact flower buds were bagged, and as soon as the flowers opened, they were emasculated and pollinated with pollen grains from different individuals; and (4) natural pollination (*n* = 14 flowers) - flowers accessible to pollinators were marked as a control. Treatments were conducted on individuals from Vale do Paraíso Farm from November 2017 to February 2018.

We used generalized linear models (GLMs) with binomial and Poisson distributions to look for treatment effects regarding the probabilities of fruit formation and number of seeds per fruit, respectively. We determined overdispersion and model fit through residual analyses (Zuur et al. 2007, Mazerolle 2019). Because we found overdispersion in the GLM with a Poisson distribution, standard errors were corrected using the dispersion parameter in a quasi-GLM. We formulated two competitive models for each response variable (Tab. 2). We fitted models to the data and ranked them according to Akaike's information criterion with a second-order bias adjustment (AICc, Burnham & Anderson 2002, Anderson 2008). We used ΔAICc, the 95% confidence interval of the regressor, Akaike's weights (AICcW), and the evidence ratio to compare the competitive models (Burnham & Anderson 2002, Anderson 2008). We conducted analyses in R 3.5.2 (R Development Core Team) using the packages AICcmodavg (Mazerolle 2019), binom (Dorai-Raj 2015), bbmle (Bolker et al. 2020), and stats (Bolar 2019).

5. *Floral visitors*

We recorded floral visitors during field observations in the mornings (7 h-10 h; *n* = four days), afternoons (15 h-18 h; *n* = three days), and evenings (18 h-21 h; *n* = three days) for two populations: Vale do Paraíso and São João farms. We categorized species as floral visitors if they touched the reproductive parts of the flowers. Floral visitors were photographed and, whenever possible, were collected, preserved in 70% alcohol, and sent to specialists for identification. We also used a camera trap (Reconyx©) to record nocturnal pollinators. The camera was placed in two different locations on the Vale do Paraíso Farm for six days, totaling 144 hours of sampling effort.

Results

1. *Species distribution modeling*

We generated a map that shows areas of high climatic suitability for *D. ferricola* based on niche modeling through the maximum entropy algorithm (AUC = 0.97; Figure 2). The TSS on the maximum threshold indicated a good fit of the final model (TSS = 0.67). The model indicated areas with adequate climates for the occurrence of *D. ferricola* in small discontinuous areas of the Serra do Amolar and on some nearby hills, as well as in the Serra da Bodoquena (Figure 2A-B). However, the greatest areas of climatic suitability for *D. ferricola* were concentrated on the hills of RPMU, specifically on the Urucum, Grande, Rabichão, São Domingos, and Mutum hills (Figure 2B).

2. *Pollinator dependence*

Only the manual cross pollination and natural pollination treatments produced fruits and, therefore, were included in the statistical analyses. The mean probability of fruit formation for natural pollination was 57% (95% CI = 33% – 79%; *n* = 14 flowers resulting in eight fruits), while for manual cross pollination, it was 85% (95% CI = 57% – 87%; *n* = 13 flowers resulting in 11 fruits). Although the estimated probability of fruit formation varied according to treatments, our data did not allow us to distinguish between the null and the alternative hypothesis of a treatment effect. That result was clear from the small values of ΔAICc (< 2.0) and the evidence ratio being close to one (Tab. 2). Regarding the number of seeds produced per fruit, our data strongly supported the hypothesis that there were more seeds in fruits that were manually pollinized. Such a result was confirmed by the large ΔAICc of the constant model (>> 7.00) and the AICcW for the treatments model (Tab. 2). The estimated mean number of seeds per fruit through manual pollination was 43 (95% IC = 36 – 52; *n* = 11), which was 2.4 times the estimated mean number of 18 seeds produced per fruit through natural pollination (95% IC = 14 – 23; *n* = 8).

3. *Floral visitors*

During the mornings, we found small beetles from the Nitidulidae family covered in pollen inside closed flowers of *D. ferricola*, which had been open the night before (Figure 3A). During the afternoons, we observed that as soon as the flower buds of *D. ferricola* emerged from the cephalium, small beetles from the Nitidulidae family pierced and penetrated them (Figure 3B). *Discocactus ferricola* flowers opened at approximately 6 p.m. (*n* = seven days) and closed at approximately 2 a.m. (*n* = five days). During the nocturnal observations, we found the same beetle species as those observed during the mornings visiting opened flowers (Figure 3C). Moreover, we found larvae of the beetles on older flowers, i.e., those that had closed on the previous days. Other species of beetles belonging to the Chrysomelidae family were found visiting the flowers and mating inside them at night (Figure 3D). Finally, using camera traps, we recorded visits of moths to the *D. ferricola* flowers. We registered four moth visits between 7 p.m. and 1 a.m. on five nights of sampling (Figure 3E and 3F). Despite these attempts, it was not possible to capture the moth species during the observations.

Discussion

1. *Species distribution modeling*

In this study, we increased the number of known populations of *D. ferricola* from three to 11 populations. With the new occurrence sites, it was possible to construct a map of climatic suitability for the occurrence of *D. ferricola* based on ecological niche modeling. The area with the highest suitability identified by the model was concentrated mainly in the RPMU, which corroborates the high environmental specificity described for *Discocactus* species (Machado et al. 2005). Most of the area with high values of climatic suitability for *D. ferricola* in the RPMU is distributed continuously. Therefore, these areas of higher environmental suitability for *D. ferricola* may also represent possible dispersal routes among populations (Figure 2). We also observed small disconnected areas with climatic suitability for *D. ferricola* in the Serra do Amolar and on some nearby hills as well as in the Serra da Bodoquena. Currently, neither GBIF nor Species Link have records of *D. ferricola* at these localities, which may be the result of undersampling due to difficulty in accessing the areas of occurrence or even of a limited dispersion capacity of this species, preventing it from colonizing these regions even with an adequate climate for its occurrence. The potential distribution map highlighted areas with higher probability of occurrence of *D. ferricola* on the Residual Plateau of Maciço do Urucum, which concentrates the largest area with the highest climatic suitability among the analyzed rock formations, probably concentrating the largest number of populations. Due to the high environmental specificity of *D. ferricola*,

Table 2. Model selection table for the probability of fruit formation and number of seeds per fruit in *Discocactus ferricola* for different reproduction treatments: natural pollination and manual cross-pollination. K: number of parameters; AICc: Akaike's information criterion with the second bias adjustment; AICcW: AICc weighted; *b* ± se: estimated beta ± standard deviations; 95% CI: 95% confidence interval for beta; ER: evidence ratio; ~ 1 (constant): model representing no differences between treatments; ~ Treatments: model representing the hypothesis of a treatment effect.

Response and models	K	ΔAICc	AICcW	*b* ± se	95% CI	ER
Fruit formation						
~ 1 (constant)	1	0.19	0.48	-	-	-
~ Treatments	2	0.00	0.52	-	-	1.1
Number of seeds*						
~ 1 (constant)	2	26.26	0.00	-	-	-
~ Treatments	3	0.00	1.00	0.89 ± 0.18	0.55 – 1.24	∞

* For the number of seeds, we used (Q)ΔAICc and (Q)AICcW. Therefore, we added one parameter (dispersion) to each model.

it is advisable that searches for new populations be carried out in areas of shallow soils, sandy or exposed rock within the areas described with relatively high values of climatic suitability to optimize time and resources (Machado et al. 2005).

Among the 11 populations sampled, only two populations of *D. ferricola* were found inside a protected area (Piraputanga Municipal Park), although the area has no maintenance, inspection or access restrictions. The other nine populations were on farms accessible to cattle and subject to fire or close to mining. Therefore, all known *D. ferricola* populations are exposed to threats like habitat loss, wildfires, and extraction for consumption as food or by collectors due to their ornamental potential. The available information about the distribution of *D. ferricola* in the Red List of Threatened Species states an area of occurrence of no more than 20 km^2 (Braun 2013). However, ironstone outcrops represent a total area of only 6.4 km^2 distributed irregularly on the RPMU (Pott et al. 2000). Thus, it is possible that the area of occurrence of *D. ferricola* is much less than 20 km^2 (Braun 2013).

2. *Pollinator dependence and floral visitors*

The absence of fruits in the self-pollination treatments may have been the result of a self-incompatible reproductive system or of extreme inbreeding depression (Mandujano et al. 2010). Despite of the cause, our results indicated that *D. ferricola* is obligatory xenogamic, and depends on the action of pollinators for effective pollination to occur. Reproductive mechanisms that act to prevent inbreeding and the consequent loss of genetic diversity are often found in species of the family Cactaceae (Mandujano et al. 2010). Xenogamy has been described for several species of cacti, including species that occur in rocky outcrops such as *Cipocereus minensis* (Werderm.) Ritter, *Uebelmannia buiningii* Donald, *Pilosocereus catingicola* (Gürke) Byles & Rowley, *P. chrysostele* (Vaupel) Byles & G.D.Rowley, and *P. pachycladus* F.Ritter (Martins et al. 2016, Teixeira et al. 2018, Rocha et al. 2020).

We found a lower number of seeds per fruit in the natural pollination treatment than in the manual pollination treatment, which suggests that the pollination function in *D. ferricola* may be inefficient due to a limitation in pollen deposition (Burd 1994, Larson & Barret 2000). This limitation could be caused by pollen of poor quality (flowers usually receive self-pollen, in addition to crossed pollen) or by the amount of pollen available (frequency of visits) (Aizen & Harder 2007). Pollen limitation is more frequent in self-incompatible species; in such cases, it is possible that the stochastic behavior of pollinators and local ecological conditions limit the activity of pollinators and are associated with reduced fertility (Burd 1994, Larson & Barret 2000). This may be the case of *D. ferricola* since we recorded only four moth visits, with flowers receiving no more than one visit, and because we found the species to be dependent on crossed pollen. Self-incompatibility and pollen limitation have also been described for *Discocactus pseudoinsignis* N.P.Taylor & Zappi and *Discocactus placentiformis* K.Schum., species that occur in Minas Gerais state, Brazil (Silveira 2015).

Flowers of *D. ferricola* were visited by two species of beetles, one from the Nitidulidae family and another from the Chrysomelidae family, and by moths from the Sphingidae family. The presence of beetles on flowers is often considered negative, as they usually act as pollen/nectar harvesters and as consumers of flowers (Pimienta-Barrios & del Castillo 2002, Martínez-Peralta & Mandujano 2011). Studies on other cactus species from outcrops, such as *Cipocereus laniflorus* N.P.Taylor & Zappi, *Pilosocereus catingicola* subsp. *salvadorensis* (Werderm.) Zappi, and *Micranthocereus purpureus* (Gürke) F.Ritter, have also found small beetles piercing flower buds serving as pollen robbers and consuming floral parts mainly during anthesis and postanthesis stages, as found for *D. ferricola* in this study (Locatelli et al. 1997, Pimienta-Barrios & Castillo 2002, Aona et al. 2006, Rego et al. 2012).

In this study, moths were the only registered nighttime visitors and they did it in a low frequency (four visits recorded from camera traps). Although we could confirm the introduction of month proboscis in the flowers, we could not affirm from photos if they touched the stigma. However, the moth likely touches the stigma due to its location within the tubular corolla and the sphingophilous syndrome (Pimienta-Barrios & del Castillo 2002, Machado et al. 2005). In addition, the time of anthesis in *D. ferricola* restricts visits from nocturnal pollinators, as the flowers are still closed during early evening. Some cacti that have nocturnal anthesis extend the anthesis period until the morning of the following day (Fleming et al. 2001), as observed by Silveira (2015) in *D. pseudoinsignis* and *D. placentiformis*, which keep flowers open until 11 a.m. of the next day, allowing visits from diurnal pollinators such as bees. Extending the anthesis period to diurnal hours increases the diversity of pollinators and may be related to greater reproductive success (Fleming et al. 2001).

Our study highlighted the benefits and practicalities of the use of ecological niche modeling and data on reproductive biology to guide new sampling efforts, identify threats, and to assist conservation and management initiatives of endangered species. Moreover, this

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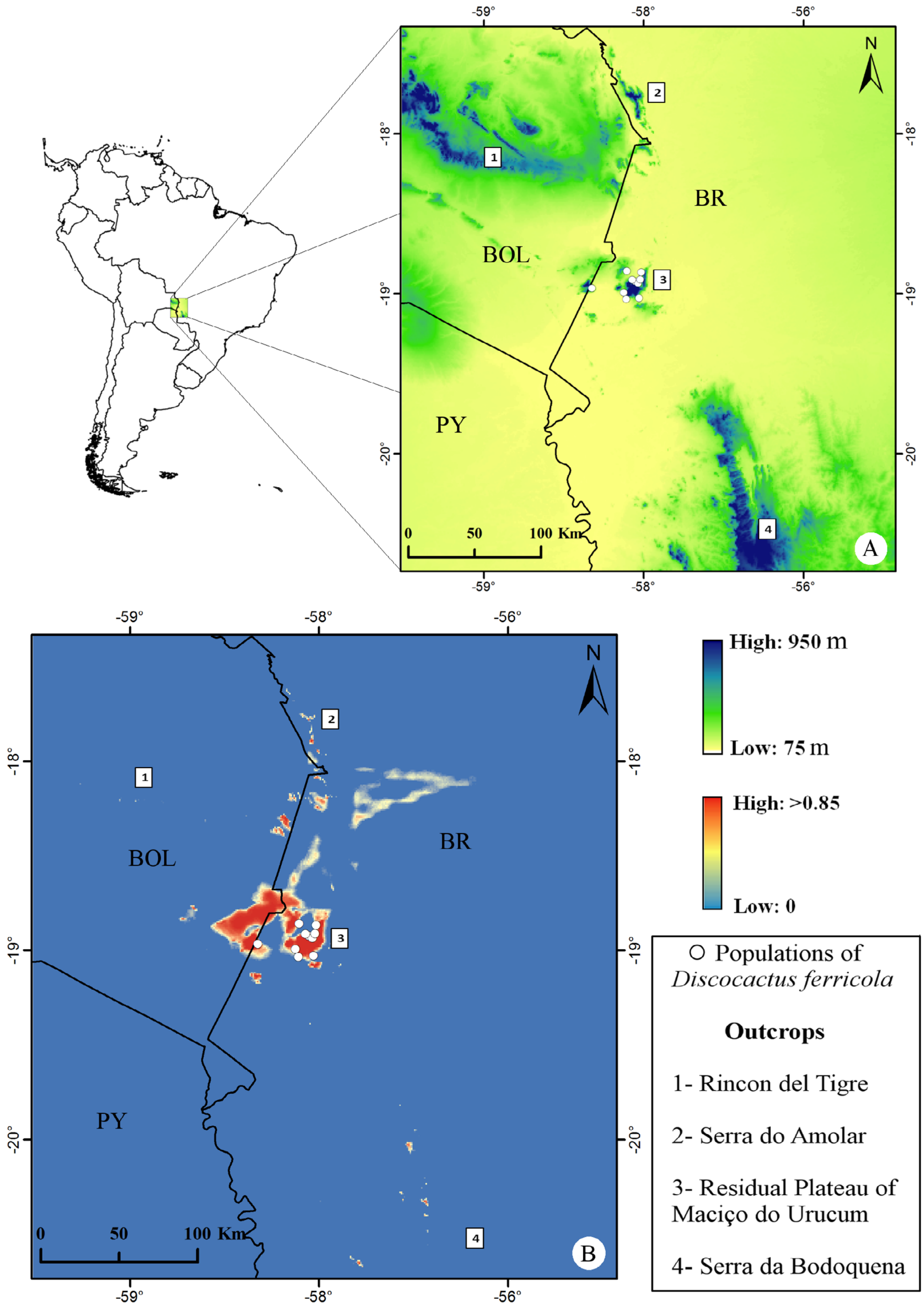

Figure 2. Geographic distribution of *Discocactus ferricola* populations. **A.** Elevation map of the area used in the modeling (background), showing the rocky outcrops of the region. **B.** Map of climatic suitability for *D. ferricola*.

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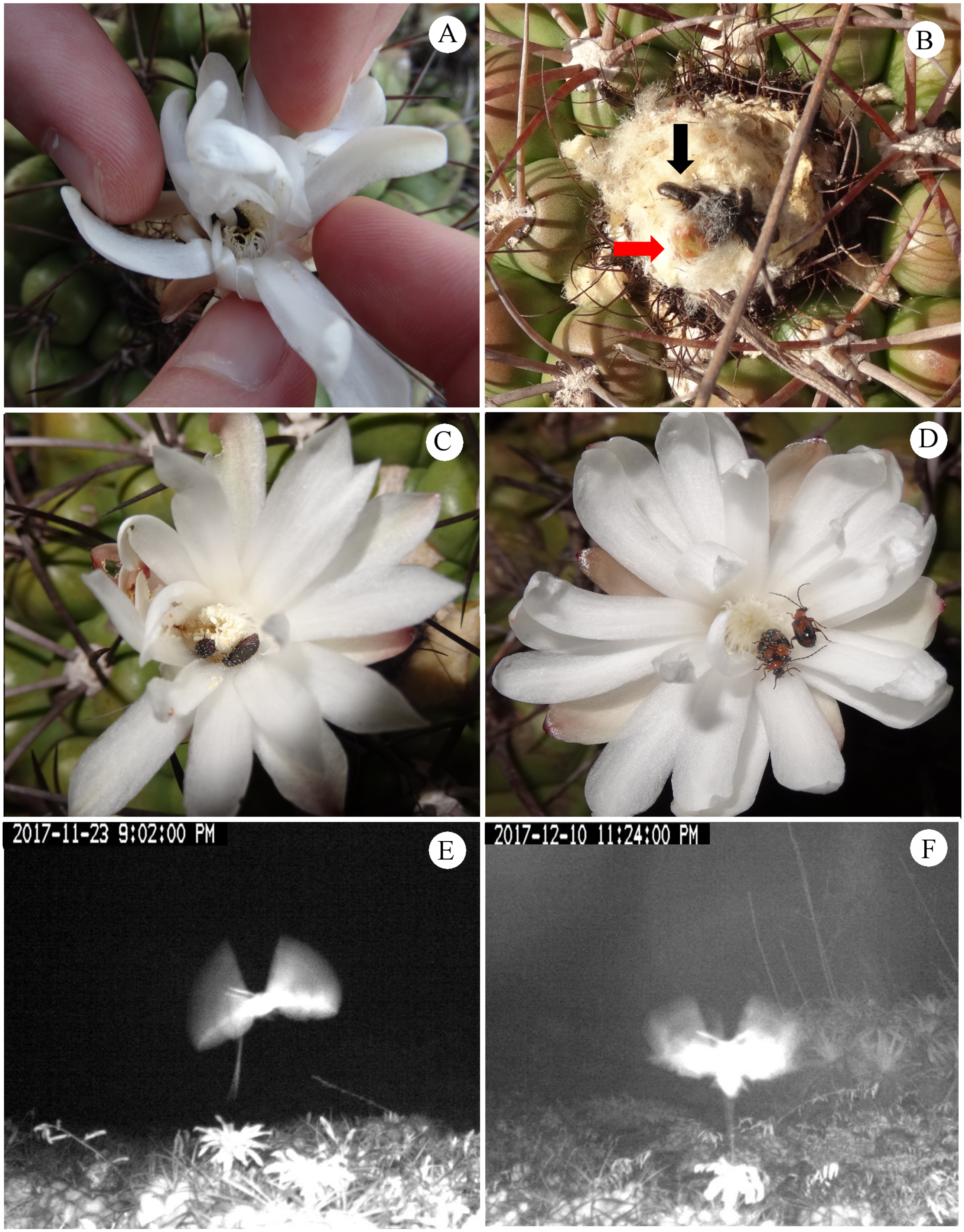

Figure 3. Pollinators recorded on *Discocactus ferricola* flowers. **A**. Beetles inside flowers after anthesis. **B.** Beetles piercing the flower buds. The black arrow points to the beetles, and the red arrow points to the floral bud starting to emerge from the cephalium. **C**. Beetles of the Nitidulidae family inside the open flowers. **D.** Beetles of the Chrysomelidae family inside the open flowers. **E-F.** Moths visiting flowers.

information allow the construction of more assertive hypotheses about the evolution and dispersion of species. The potential distribution map showed that the RPMU represents the largest and most important area of distribution of *D. ferricola*, concentrating the largest number of populations. We also found small disconnected areas with climatic suitability for *D. ferricola* in the Serra do Amolar and the Serra da Bodoquena, which represents potential areas for future sampling.

Strengthening public policies for *in situ* and *ex situ* conservation of threatened species of cactus should be in the spotlight of conservation plans. For *D. ferricola*, *in situ* conservation actions should prioritize the maintenance of interactions with pollinators by preserving flora and fauna of rocky outcrops and adjacent forests. For that, there is the need for revitalization and implementation of reserves, parks, and ecological corridors in areas of greater environmental suitability. As *ex situ* actions, we recommend the expansion of inspection activities by environmental authorities concerning the illegal trade of threatened and endemic species. Our approach and results may assist in the evaluation and implementation of more efficient conservation actions for rare and endangered species, especially for *D. ferricola*.

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Conflicts of Interest

The authors declare that they have no conflict of interest related to the publication of this manuscript.

References

ADHIKARI, D., TIWARY, R., SINGH, P.P., UPADHAYA, K., SINGH, B., HARIDASAN, K.E., BHATT, B.B., CHETTRI, A. & BARIK, S.K. 2019. Ecological niche modeling as a cumulative environmental impact assessment tool for biodiversity assessment and conservation planning: A case study of critically endangered plant *Lagerstroemia minuticarpa* in the Indian Eastern Himalaya. J. Environ. Manage. 243:299-307.

AIZEN, M.A. & HARDER, L.D. 2007. Expanding the limits of the pollen-limitation concept: effects of pollen quantity and quality. Ecology 88(2):271-281.

ALLOUCHE, O., TSOAR, A. & KADMON, R. 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). J. Appl. Ecol. 43(6):1223-1232.

ANDERSON, D.R. 2008. Model Based Inference in the Life Sciences: a Primer on Evidence. Springer Science + Business Media, New York.

ANDERSON, E.F. 2001. The cactus family. Timber Press, Portland.

ANDERSON, R.P. & GONZALEZ, J.I. 2011. Species-specific tuning increases robustness to sampling bias in models of species distributions: an implementation with Maxent. Ecol. Model. 222(15):2796-2811.

AONA, L.Y.S., MACHADO, M., PANSARIN, E.R., DE CASTRO, C.C., ZAPPI, D. & MARIA DO CARMO, E. 2006. Pollination biology of three Brazilian species of *Micranthocereus* Backeb. (Cereeae, Cactoideae) endemic to the “campos rupestres”. Bradleya 2006(24): 39-52.

BIVAND, R., KEITT, T. & ROWLINGSON, B. 2018. rgdal: Bindings for the ‘Geospatial’ Data Abstraction Library. R package version 1.3-6. https://CRAN.R-project.org/package=rgdal

BOLAR, K. 2019. STAT: interactive document for working with basic statistical analysis. R package.

BOLKER, B., R DEVELOPMENT CORE TEAM & GINÉ-VÁZQUES, I. 2020. bbmle: tools for general Maximum likelihood estimation. R package.

BRAUN, P. 2013. The IUCN Red List of Threatened Species 2013: *Discocactus ferricola*. Available: https://dx.doi.org/10.2305/IUCN.UK.2013-1.RLTS.T151934A578020.en.

BROWN, J.H. 1995. Macroecology. University of Chicago Press, Chicago.

BURD, M. 1994. Bateman’s Principle and plant reproduction: The role of pollen limitation in fruit and seed set. Bot. Rev. 60(1):83-139.

BURNHAM, K.P. & ANDERSON, DR. 2002. Model selection and multimodel inference: a practical information-theoretic approach. 2 ed. Springer Science + Business Media, New York.

DORAI-RAJ, S. 2015. binom: binomial confidence intervals for several parameterizations. R package.

ESRI. 2014. ArcGIS Desktop: Release 10.3. Environmental Systems Research Institute, Redlands.

FICK, S.E. & HIJMANS, R.J. 2017. Worldclim 2: New 1-km spatial resolution climate surfaces for global land areas. Int. J. Climatol. 37(12):4302-4315.

FISCHER, G., NACHTERGAELE, F., PRIELER, S., VAN VELTHUIZEN, H. T., VERELST, L. & WIBERG, D. 2008. Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008). IIASA Austria and Rome, FAO, Laxenburg.

FLEMING, T. H., SAHLEY, C. T., HOLLAND, J. N., NASON, J. D. & HAMRICK, J. L. 2001. Sonoran Desert columnar cacti and the evolution of generalized pollination systems. Ecol. Monogr. 71(4):511-530.

FOIS, M., CUENA-LOMBRAÑA, A., FENU, G. & BACCHETTA, G. 2018. Using species distribution models at local scale to guide the search of poorly known species: Review, methodological issues and future directions. Ecol. Model. 385:124-132.

HIJMANS, R.J. 2018. Raster: Geographic Data Analysis and Modeling. R package version 2.8-4. https://CRAN.R-project.org/package=raster

KOLANOWSKA, M. & JAKUBSKA-BUSSE, A. 2020. Is the lady’s-slipper orchid (*Cypripedium calceolus*) likely to shortly become extinct in Europe?—Insights based on ecological niche modelling. PLoS One 15(1):e0228420.

LARSON, B.M.H. & BARRET, S.C.H. 2000. A comparative analysis of pollen limitation in flowering plants. Biol. J. Linn. Soc. 69(4):503-520.

LE LAY, G., ENGLER, R., FRANC, E. & GUISAN, A. 2010. Prospective sampling based on model ensembles improves the detection of rare species. Ecography 33(6):1015-1027.

LIMA-RIBEIRO, M.S. & DINIZ-FILHO, J.A.F. 2013. Modelos ecológicos e a extinção da megafauna: clima e homem na América do Sul. Cubo, São Carlos.

LOCATELLI, E., MACHADO, I.C. & MEDEIROS, P. 1997. Floral biology and bat pollination in *Pilosocereus catingicola* (Cactaceae) in northeastern Brazil. Bradleya 15:28-34.

LÜTHY, J.M. 2001. CITES identification manual: The cacti of CITES appendix I. CITES, Federal Veterinary Office Switzerland, Botanical Garden of the University of Berne, IOS & Sukulent-Sammlung *Zürich, Bern*.

MACHADO, M.C., ZAPPI, D.C., TAYLOR, N.P. & BORBA EL. 2005. Taxonomy and conservation of the *Discocactus* Pfeiff. (Cactaceae) species occurring in the state of Bahia, Brazil. Bradleya 23:41-57.

MACHADO, M.C. 2004. O gênero *Discocactus* Pfeiff. (Cactaceae) no estado da Bahia, Brasil: variabilidade morfológica, variabilidade genética, taxonomia e conservação. MSc Thesis, Universidade Estadual de Feira de Santana, Feira de Santana. PPGBot. http://www.ppgbot.uefs.br (last access in 04/07/2020).

MANDUJANO, M.C., CARRILLO-ANGELES, I., MARTÍNEZ-PERALTA, C. & GOLUBOV, J. 2010. Reproductive biology of Cactaceae. In Desert Plants (K.G. Ramawat, ed.) Springer, Berlin/ Heidelberg, p.197-230.

MARTINELLI, G. & MORAES, M.A. 2013. Livro vermelho da flora do Brasil. Instituto de Pesquisas Jardim Botânico do Rio de Janeiro, Rio de Janeiro.

MARTINEZ-MEYER, E., PETERSON, A.T., SERVÍN, J.I. & KIFF, L.F. 2006. Ecological niche modelling and prioritizing areas for species reintroductions. Oryx 40(4):411-418.

MARTÍNEZ-PERALTA, C. & MANDUJANO, M.C. 2011. Reproductive ecology of the endangered living rock cactus, *Ariocarpus fissuratus* (Cactaceae). J. Torrey Bot. Soc. 138(2):145-155.

MARTINS, C., OLIVEIRA, R., MENDONÇA FILHO, C.V., LOPES, L.T., SILVEIRA, R.A., DE SILVA, J.A.P., AGUIAR L.M.S. & ANTONINI, Y. 2016. Reproductive biology of *Cipocereus minensis* (Cactaceae)—A columnar cactus endemic to rupestrian fields of a Neotropical savannah. Flora 218:62-67.

MAZEROLLE, M.J. 2019. AICcmodavg: model selection and multimodel inference based on (Q)AIC(c). R package.

MCCUNE, J.L. 2016. Species distribution models predict rare species occurrences despite significant effects of landscape context. J. Appl. Ecol. 53(6):1871-1879.

NENZÉN, H.K. & ARAÚJO, M.B. 2011. Choice of threshold alters projections of species range shifts under climate change. Ecol. Model. 222(18):3346-3354.

OKSANEN, J., BLANCHET, F.G., FRIENDLY, M., KINDT, R., LEGENDRE, P., MCGLINN, D., MINCHIN, P. R., O'HARA, R.B., SIMPSON, G. L, SOLYMOS, P., STEVENS, M. H.H., SZOECS, E. & WAGNER, H. 2018. Vegan: Community Ecology Package. R package version 2.5-3. https://CRAN.R-project.org/package=vegan

PETERSON, A. T., SOBERÓN, J., PEARSON, R. G., ANDERSON, R. P., MARTÍNEZ-MEYER, E., NAKAMURA, M. & ARAÚJO, M. B. 2011. Ecological niches and geographic distributions. Princeton University Press, Princeton.

PETERSON, A.T. & SOBERÓN, J. 2012. Species distribution modeling and ecological niche modeling: getting the concepts right. Nat. Conservação 10(2):1-6.

PHILLIPS, S.J., ANDERSON, R.P., & SCHAPIRE, R.E. 2006. Maximum entropy modeling of species geographic distributions. Ecol. Model. 190(3-4):231-259.

PIMIENTA-BARRIOS, E., & DEL CASTILLO, R.F. 2002. Reproductive Biology. In Cacti: Biology and Uses (P.S. Nobel, ed.). University of California, London, p.75- 90.

PORFIRIO, L.L., HARRIS, R.M., LEFROY, E.C., HUGH, S., GOULD, S.F., LEE, G., BINDOFF, N.L. & MACKEY, B. 2014. Improving the use of species distribution models in conservation planning and management under climate change. PLoS One 9(11):e113749.

POTT, A., SILVA, J.S.V., SALIS, S.M., POTT, V. & SILVA, M.D. 2000. Vegetação e uso da terra. In Zoneamento ambiental da Borda Oeste do Pantanal: Maciço do Urucum e Adjacências (J.S.V. Silva, ed.). Embrapa, Brasília, p. 111-131.

QIAO, H., ESCOBAR, L.E. & PETERSON, A.T. 2017. Accessible areas in ecological niche comparisons of invasive species: Recognized but still overlooked. Sci. Rep-Uk 7(1):1-9.

R CORE TEAM. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. https://www.r-project.org/.

REGO, J.O., FRANCESCHINELLI, E.V. & ZAPPI, D.C. 2012. Reproductive biology of a highly endemic species: *Cipocereus laniflorus* N.P. Taylor & Zappi (Cactaceae). Acta Bot. Bras. 26(1):243-250.

RIBEIRO-SILVA, S., ZAPPI, D.C., TAYLOR, N.P. & MACHADO, M.C. 2011. Plano de Ação Nacional para a conservação das Cactáceas. Série Espécies Ameaçadas nº 24. Instituto Chico Mendes de Conservação da Biodiversidade, Ministério do Meio Ambiente, Brasília.

ROCHA, E.A., DOMINGOS-MELO, A., ZAPPI, D.C., & MACHADO, I.C. 2020. Reproductive biology of columnar cacti: are bats the only protagonists in the pollination of *Pilosocereus*, a typical chiropterophilous genus?. Folia Geobot. 54: 239-256.

SCHEELE, B.C., LEGGE, S., ARMSTRONG, D.P., COPLEY, P., ROBINSON, N., SOUTHWELL, D., WESTGATE M.J. & LINDENMAYER D.B. 2018. How to improve threatened species management: an Australian perspective. J. Environ. Manage. 223:668-675.

SILVEIRA R.A. 2015. Ecologia de *Discocactus pseudoinsignis* e *Discocactus placentiformis* simpátricos e endêmicos da Serra do Espinhaço, MG, Brasil. MSc Thesis, Universidade Federal de Ouro Preto, Ouro Preto. UFOP. http://www.repositorio.ufop.br (last access 06/09/2020).

SOBERÓN, J. & PETERSON, A.T. 2005. Interpretation of models of fundamental ecological niches and species' distributional areas. Biodivers. Inform. 2:1-10.

SOBRAL-SOUZA, T., VANCINE, M.H., RIBEIRO, M.C. & LIMA-RIBEIRO, M.S. 2018. Efficiency of protected areas in Amazon and Atlantic Forest conservation: A spatio-temporal view. Acta Oecol. 87:1-7.

SORIANO, B.M.A. 2000. Climatologia. In Zoneamento ambiental da Borda Oeste do Pantanal: Maciço do Urucum e Adjacências (J.S.V. Silva ed.). Embrapa, Brasília, p. 69-82.

TAKAHASI, A. & MEIRELLES, S.T. 2014. Ecologia da vegetação herbácea de bancadas lateríticas (cangas) em Corumbá, MS, Brasil. Hoehnea 41(4):515-528.

TEIXEIRA, V. D., VEROLA, C. F., DA COSTA, I. R., ZAPPI, D. C., DA COSTA, G. M., SILVA, S. R., COSTA M.A.P.C. & AONA, L.Y.S. 2018. Investigating the floral and reproductive biology of the endangered microendemic cactus *Uebelmannia buiningii* Donald (Minas Gerais, Brazil). Folia Geobot. 53(2):227-239.

VARELA, S., ANDERSON, R.P., GARCÍA-VALDÉS, R. & FERNÁNDEZ-GONZÁLEZ, F. 2014. Environmental filters reduce the effects of sampling bias and improve predictions of ecological niche models. Ecography 37(11):1084-1091.

VASCONCELOS, P.M., FARLEY, K.A., STONE, J., PIACENTINI, T. & FIFIELD, L.K. 2019. Stranded landscapes in the humid tropics: Earth's oldest land surfaces. Earth Planetary Sc. Let. 519:152-164.

WERNECK, F.P., NOGUEIRA, C., COLLI, G.R., SITES JUNIOR J.W. & COSTA, G.C. 2012. Climatic stability in the Brazilian Cerrado: implications for biogeographical connections of South American savannas, species richness and conservation in a biodiversity hotspot. J. Biogeogr. 39(9):1695-706.

ZHU, J., XU, X., TAO, Q., YI, P., YU, D. & XU, X. 2017. High invasion potential of *Hydrilla verticillata* in the Americas predicted using ecological niche modeling combined with genetic data. Ecol. Evol. 7(13):4982-4990.

ZUUR, A.F., IENO, E.N. & SMITH, G.M. 2007. Analysing Ecological Data. Springer Science + Business Media, New York.

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