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MODELING THE POTENTIAL DISTRIBUTION OF *Anamaria heterophylla* (GIUL. & V.C. SOUZA) V.C. SOUZA (PLANTAGINACEAE) IN THE CAATINGA

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Abstract: Species distribution modeling (SDM) is a tool with several ecological applications, including predicting biological invasions and indicating environmentally appropriate areas for the occurrence of endemic or endangered species. The Caatinga endemic plant species *Anamaria heterophylla* (Plantaginaceae) is of rare occurrence and lives in ecologically vulnerable aquatic environments; the species is used as a parameter for the selection of Priority Areas for the Conservation of the Caatinga (PACCs). The objectives of this study were to estimate its potential geographic distribution and the climatic conditions across its distributional range, as well as to identify suitable areas for its occurrence, aiming to evaluate the efficiency of the current Protected Areas (PAs) and PACCs network as to the protection of the species. We developed SDM for *A. heterophylla* using the MaxEnt algorithm, based on 26 occurrence points, and evaluated the importance of environmental variables and the predictive ability of the generated distribution models. Our results predicted that the distribution of *A. heterophylla* is tightly guided by conditions of high aridity and low annual precipitation. The potential distribution model indicated three broad areas with high environmental suitability (probability of presence ≥ 0.8): one in the western of the state of Ceará, one between northern Bahia and western Pernambuco states, and another between the central region of the states of Rio Grande do Norte and Paraíba, which overlap in large part the Caatinga regions where temporary ponds (primary habitat of *A. heterophylla*) are numerous. We found out that nine areas of the PAs and PACCs network of protecting areas presented high environmental suitability, as indicated by the SDM. Based on these findings, we recommend that future collection efforts for *A. heterophylla* focus on the key locations identified through the SDM, and we hope that this may serve to support future actions regarding the selection of important areas for biodiversity conservation in the Caatinga.

Keywords: conservation of biodiversity; semiarid; species distribution modeling; temporary ponds.

INTRODUCTION

The recognition of the environmental conditions and resources that influence the spatial distribution of a particular species can help to characterize potential niches for its survival and reproduction (Kamino *et al.* 2011). In this context, the correlative modeling of potential geographic distributions of species, or species distribution modeling (SDM), has emerged as an important tool for studies of biogeography, evolution and conservation biology (Myers *et al.* 2000, Guisan & Thuiller 2005, Cayuela *et al.* 2009, Kamino *et al.* 2012).

Species distribution modeling is a procedure by which a mathematical algorithm optimizes (correlates) the occurrence sites of a target species with environmental information from these sites and, as a product of these correlations, indicates suitable environments for the species' survival (Anderson *et al.* 2003, Guisan & Thuiller 2005). Among the studies that use SDM in the context of conservation biology, those that can identify new populations of rare, endemic and/or threatened species from model-predicted areas are of particular relevance (Araújo & Williams 2000, Engler *et al.* 2004, Siqueira *et al.* 2009, Hassemer *et al.* 2015, Alencar *et al.* 2018).

Anamaria heterophylla (Giul. & V.C. Souza) V.C. Souza (Plantaginaceae) is an endemic plant species of the Caatinga, of rare occurrence, restricted to environments such as margins of lakes or temporary ponds (Souza 2001, Giulietti *et al.* 2003a, Campelo *et al.* 2012, Campelo *et al.* 2013, Siqueira-Filho 2012, Souza *et al.* 2017). Due to its endemic nature and limited occurrence in intermittent environments, it has been suggested that *A. heterophylla* should integrate the list of Brazilian threatened species and be used in the evaluation of Priority Areas for the Conservation of the Caatinga (PACCs) (Giulietti *et al.* 2003b, Siqueira-Filho 2012, MMA 2016a).

Although there are known records for *A. heterophylla* in eight of the nine states of the Northeastern Region of Brazil (except Maranhão state), and this species is known to occur in all ecoregions of the Caatinga (Siqueira-Filho 2012, Campelo *et al.* 2013, Souza *et al.* 2017, SpeciesLink 2018), there are no studies indicating habitat specificities and/or suitable bioclimatic conditions for the occurrence of the species in the Caatinga region. In this situation, the SDM tool allows characterizing environmental conditions.

Understanding the potential geographic distribution of *A. heterophylla* from SDM also allows the recognition of PACCs and Protected Areas (PAs) of the Caatinga that, despite lacking records for the species, possess environmental suitability for its occurrence. New records of *A. heterophylla* for these PACCs and/or PAs would foster future discussions on the implementation/effectuation of PACCs and reassessments of possible constraints in the access and use of PAs by society. Also, new records of *A. heterophylla* from SDM in the Caatinga could support future evaluation and selection of new PACCs and PAs in the region.

Therefore, the present study models the distribution of *A. heterophylla* in the Caatinga and tests the performance of the resulting model. The good performance of the model allowed its use to: (*i*) infer suitable environmental conditions for *A. heterophylla* in the Caatinga; (*ii*) indicate habitats that present similar environmental conditions to those of the known occurrence sites of the species; and (*iii*) identify PACCs and PAs that present favorable environmental conditions for the occurrence of *A. heterophylla*, even if there are no confirmed records of the species for them.

MATERIAL AND METHODS

Dataset

Anamaria is a monospecific genus (Souza 2001), with *A. heterophylla* being distinguished from all other species of its family by being heterophyllous and possessing acrodromous venation and inflorescence with ramifications in dichasium (Souza 2001) (Supplementary Material 1).

The records used in the SDM of *A. heterophylla* for the Caatinga were obtained from data of the Brazilian herbarium network, available on SpeciesLink (2018), and from the global plant database maintained by the Global Biodiversity Information Facility (www.gbif.org; GBIF.org 2018). Scientific papers in Scopus, Web of Science, Scielo, and Google Scholar indexed journals were also consulted to broaden the search for records of the species. Such papers had to contain in their title, abstract or main body text the following combinations of words: "*Anamaria heterophylla* (Giul. & V.C. Souza) V.C. Souza", "*Anamaria heterophylla*", "*A. heterophylla*", or its synonym "*Stemodia heterophylla*". However, all records thus found for the species, cited in scientific papers, were already listed in the SpeciesLink and GBIF databases.

Were considered as accurate the data whose geographic coordinates of the specimen/exsiccatae were referenced in the collection spot, excluding the georeferenced spots for municipal seats and dubious taxonomical identification (De Marco Jr. & Siqueira 2009, Kamino *et al.* 2011). Moreover, duplicate geographic coordinates or spots that were separated by a minimum of two kilometers were excluded to avoid spatial autocorrelation bias (De Marco-Júnior & Siqueira 2009, Kamino *et al.* 2011, Giannini *et al.* 2012). Thus, 26 records for *A. heterophylla* understood the above filters (Supplementary Material 2).

Selection of variables

Climate layers that summarize general information on precipitation, temperature, and geomorphological features are often employed in studies aimed at approximating the geographic distribution potential of endemic plant species in the Caatinga (Maciel *et al.* 2012, Moura-Júnior *et al.* 2016). Therefore, nineteen bioclimatic environmental layers were cut out for the Caatinga from the WorldClim 2.0 dataset, using the ARCGIS geographic information system (version 10.2) (Fick & Hijmans 2017). Furthermore, evapotranspiration and aridity index layers from CGIAR-CSI (Zomer *et al.* 2007) and elevation and slope layers from the National Institute of Space Research of Brazil (INPE 2016) were also employed to build our model. All the environmental layers used in this study had a resolution of 30 seconds (~1 km^2 per pixel).

Principal component analysis (PCA) was employed to select some of the environmental layers in order to compute the SDM for *A.heterophylla*. The selection of variables aimed at minimizing multicollinearity and avoiding excessive parameterization of the model due to redundant variables (Peterson *et al.* 2007, Dormann *et al.* 2013, Mellin *et al.* 2010, Moura-Júnior *et al.* 2016). PCA has been recognized as useful for selecting environmental variables in macroecological studies because it is able to detect complex relationships between these variables that cannot be clarified through other statistical analyses, such as variance inflation value or correlation matrix (Eisenlohr 2014). The overlapping inclusion of environmental layers in SDM can complicate the interpretation of the importance and effect of each variable (environmental layer) in the model (Heikkinen *et al.* 2004, De Marco-Júnior & Siqueira 2009, Kamino *et al.* 2011, Giannini *et al.* 2012, Moura-Júnior *et al.* 2016).

The PCA was performed using a data matrix comprising the values recorded through the ARCGIS geographic information system (version 10.2) for each pixel of the environmental layers. The first four main components of the PCA were selected, since together they account for more than 85% of the variation of the environmental variables (layers). The environmental variables that maximized the percentage explained by each PCA component were then selected for SDM, namely: average temperature of the coldest quarter (bio11), annual precipitation (bio12), precipitation seasonality (bio15) and aridity index (ai) (Supplementary Material 3 and 4). The PCA was computed using the Vegan package version 2.2.1 (Oksanen *et al.* 2015) of the R software, version 3.3.2 (R Core Team 2016).

Species distribution model

The predictive performance of SDMs can vary significantly with the choice of modeling method (Hao *et al.* 2019). Some works cite the superior predictive performance of ensembles over individual models (as seen in Crossman & Bass 2008, Marmion *et al.* 2009) as justification for choosing them. However, individual models have also shown to outperform ensemble models (Crimmins *et al.* 2013). Due to the characteristics of the data in this study, all models were run using the MaxEnt algorithm (Phillips *et al.* 2006). The Maximum Entropy algorithm (MaxEnt - Phillips *et al.* 2006) was employed to perform SDM since it is especially useful for species that contain a low known number of occurrence points, and also because it requires only presence points (and not absence points, such as occurs in other algorithms) (Wisz *et al.* 2008), which is our case.

Using MaxEnt we randomly partitioned the 26 occurrence records of *A. heterophylla* into 70% for calibration (or training), and 30% for validation (or testing), and repeated this process 10 times through the bootstrap method in order to calculate an average model of habitat suitability probability (Phillips *et al.* 2004, Phillips *et al.* 2006, Hoveka *et al.* 2016). In order to determine the accuracy of the resulting models, we computed the average value of the Area Under the Curve (AUC) of the Receiver Operating characteristic Curve (ROC) of the ten optimization procedures, and converted continuous predictions into presence and absence, by adopting the threshold Minimum Training Presence to calculate the True Skill Statistics (TSS) (Allouche *et al.* 2006). The AUC varies from 0 to 1: a score of 1 corresponds to perfect discrimination, whereas a score of 0.5 is no different from random (Fielding & Bell 1997). TSS values range from -1 to 1; when the values are negative or close to zero, the models are not different of a randomly generated model; models with values close to 1 are considered excellent. In general, acceptable models present TSS values over 0.5 (Allouche *et al.* 2006). Such statistics have been previously used in the evaluation of SDM performance for aquatic species on a regional scale (Lehtonen 2009, Mukherjee *et al.* 2011, Moura-Júnior *et al.* 2016, Bosso *et al.* 2017, Lopes *et al.* 2017).

The resulting average model of the ten optimization procedures of the MaxEnt logistic output is a continuous map, indexing the environmental suitability of *A. heterophylla* with values ranging from cut-off threshold (Minimum Training Presence) to the maximum environmental suitability. For further analysis, the MaxEnt results were imported into ArcGIS 10.2, and the two classes of environmental suitability were grouped as moderate suitability (< 0.8) and high suitability (≥ 0.8).

The SDM provided logistic prediction curves that allowed the evaluation of the type of relationships between the occurrence of *A. heterophylla* and the environmental variables (layers) selected by the PCA. The SDM also provided the Jackknife procedure that allowed us to evaluate the contribution of each environmental variable in the model (Figure 1).

The SDM was overlapped with layers of PACCs (MMA 2016a), PAs (MMA 2016b) and state boundaries (IBGE 2016) in order to indicate habitats that present similar environmental conditions to those of the known occurrence sites of the species. It also allowed to identify the PACCs and PAs that possess favorable environmental conditions to the occurrence of *A. heterophylla*, even in the absence of confirmed records for the species. The ARCGIS 10.2 was used to develop thematic maps.

RESULTS

Prediction curves of the variables used in the SDM revealed that within the Caatinga climatic conditions gradient, *A. heterophylla* is adjusted to occur in habitats with high aridity (ai < 0.60) and low annual precipitation (bio12 < 1100 mm) (Figures 1a and 1b). Habitats with higher seasonality as to precipitation (bio15 > 40) and higher temperatures in the colder months (bio11 > 18C°) also increase the occurrence probability of *A. heterophylla*, although they demonstrated to be less important for our SDM (Figures 1c and 1e).

The potential distribution model of *A. heterophylla* exhibited a good predictive performance (AUC = 0.847 ± 0.021 and TSS = 0.583 ± 0.0844). With the application of a Minimum Training Presence threshold of 0.199 ± 0.099, the SDM indicated continuous and semi-continuous environmentally suitable areas for the presence of *A. heterophylla,* with 492,447.54 km^2, the equivalent to 59.53% of the background (Supplementary Material 5). This area extends from the coastal region of the state of Rio Grande do Norte to north-central and western state of Bahia, southeastern and eastern state of Piauí and northern state of Ceará, in addition to isolated areas from southern state of Bahia to the north of the state of Minas Gerais (Figure 2a). Out of the Northeastern Brazilian states, only the state of Maranhão had no SDM-indicated areas. Locations with high environmental suitability (≥ 0.8) were identified in three large areas: the central region of the states of Rio Grande do Norte and Paraíba; the northern region of the state of Bahia and western region of state of Pernambuco; and the western portion of the state of Ceará, with approximately 4,306, 15,438 and 5,909 km^2, respectively (Figure 2a).

The SDM indicated areas of 74 Caatinga PAs, which together represent 7.25% of all the area indicated by the model as environmentally suitable for the occurrence of *A. heterophylla*. Among these PAs, the Full Protection areas Serra of Areal, Aiuaba, Tatu-Bola, Riacho Pontal and the sustainable use area of the Sobradinho Lake stand out for possessing areas with high environmental suitability (≥ 0.8) for the potential distribution of *A. heterophylla*. However, the relevance of the area extension of the Sobradinho Lake indicated by the model is highlighted, with approximately 12,373.65 km^2 (Figure 2a).

Of the total area predicted by the SDM as suitable for the potential occurrence of *A. heterophylla*, 33.12% overlapped 211 PACCs, of which 26 had high environmental suitability (≥ 0.8) for the occurrence of *A. heterophylla*. Among these, the PACCs of Serra de Santa Luzia, Parambú/Cococi, Petrolina and Juazeiro Sul stand out, since each had more than 50% of its area predicted by SDM, with high environmental suitability (≥ 0.8; Figure 2b).

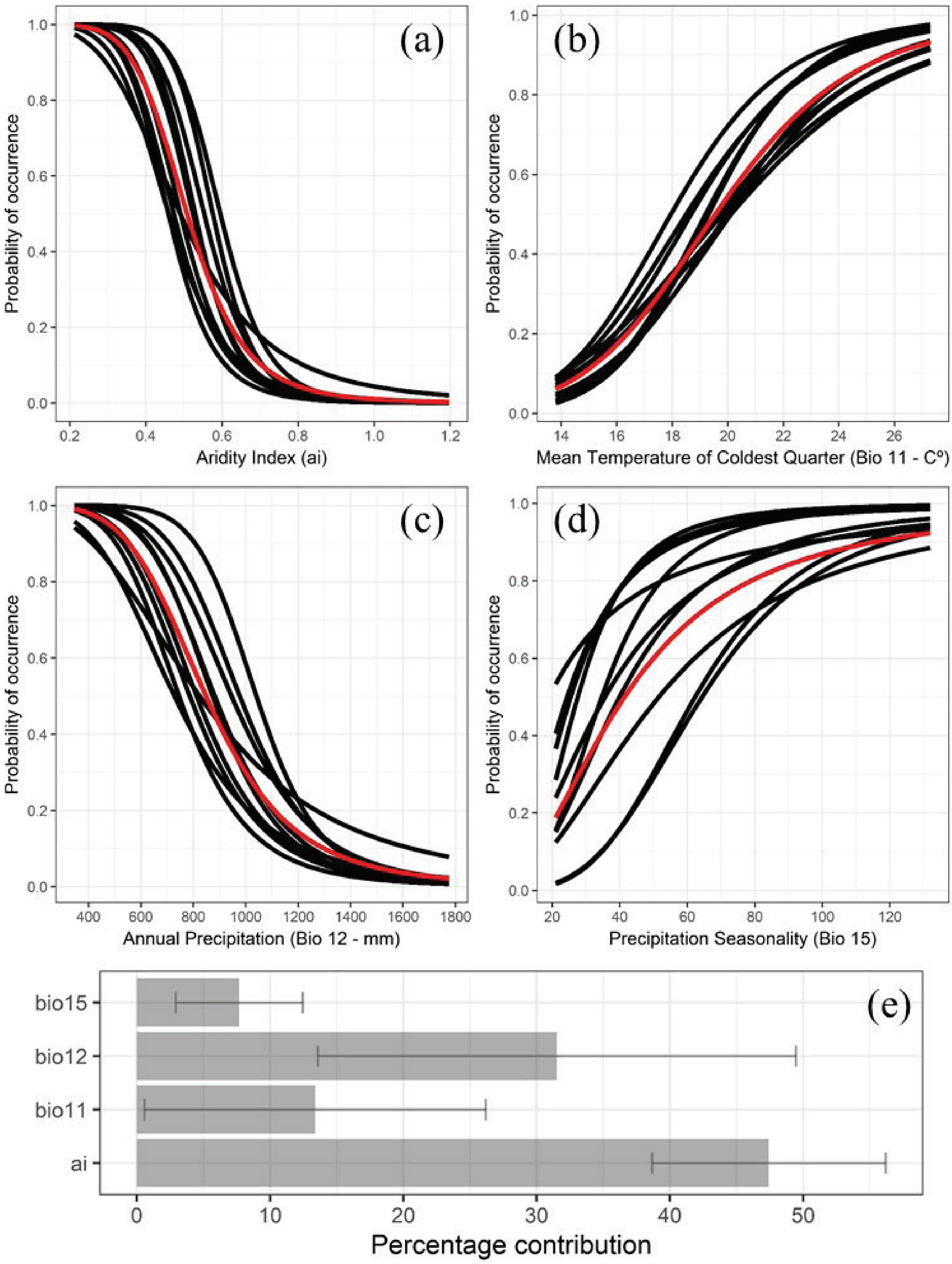

Figure 1. Prediction curves and percentage contribution of the best set of predictive variables in species distribution modeling. In figures a-d the black lines represent the ten optimization procedures and the red line the average model. **(a)** Aridity Index; **(b)** Mean Temperature of Coldest Quarter; **(c)** Annual Precipitation; **(d)** Precipitation Seasonality; **(e)** Percentage contribution of each variable.

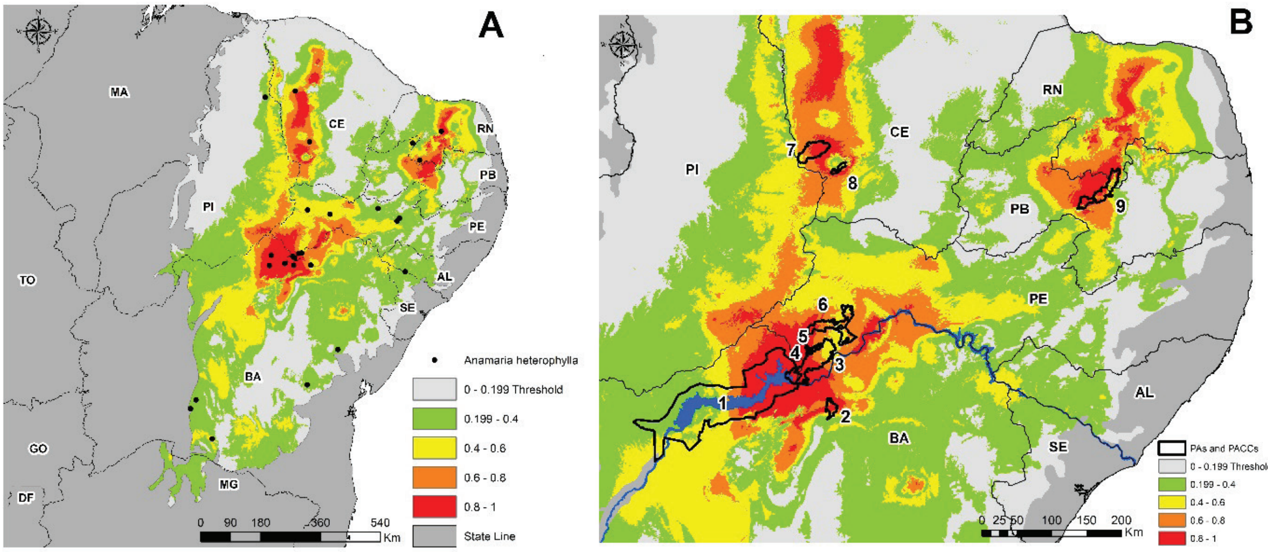

Figure 2. Species Distribution Modeling of *Anamaria heterophylla* (Plantaginaceae) for the Caatinga. **(a)** The boundaries of the Brazilian Federative Units. Al - Alagoas; BA - Bahia; CE - Ceará; DF - Distrito Federal; GO - Goiás; MA - Maranhão; MG - Minas Gerais; PB - Paraíba; PE - Pernambuco; PI - Piauí; RN - Rio Grande do Norte; SE - Sergipe; TO - Tocantins. **(b)** Protected Areas (PAs) and Priority areas for the conservation of the Caatinga (PACCs) indicated by SDM with high environmental suitability (≥0.8) in the Caatinga. 1 - PA Pond of Sobradinho (BA); 2 - PACC Juazeiro Sul (BA); 3 - PACC Petrolina (PE/BA); 4 - PA Riacho Pontal (PE); 5 - PA Serra of Areal (PE); 6 - PA Tatu-Bola (PE); 7 - PACC Parambú/Cococi (CE); 8 - PA Aiuaba; 9 - PACC Serra de Santa Luzia (PB/RN).

DISCUSSION

From the prediction curves for the variables with most significant explanation in the SDM (aridity index and annual precipitation), it can be inferred that the environmental niche of *A. heterophylla* is best adjusted, in the bioclimatic point of view, to environments vulnerable to the maintenance/duration of ponds due to reduced rainfall and high evapotranspiration rates, which is expected, given its habit.

Some studies have indicated that the intensity and duration of precipitation and evapotranspiration are related to limnological characteristics (Hammer 1986, Moura-Júnior *et al.* 2015, Moura-Júnior *et al.* 2016), such as transparency, turbidity and salinity, for example. In other words, situations of large temporal variation in limnological conditions make the photosynthetic processes of aquatic plants more complex (Wetzel 2001, Esteves 2011). In environments of low rainfall and high evapotranspiration, such as in the Caatinga, higher transparency and lower turbidity are expected in temporary ponds, due to the lower amount of suspended solids during drought, considerably increased with rainfall inflow (Thomaz *et al.* 2007). On the other hand, high aridity conditions can alter the physical-chemical characteristics of aquatic environments, accelerating the evapotranspiration rates that increase the concentrations of salts during drought. This latter factor is even more important in the Caatinga, which presents a high proportion of poorly drained soils with high concentrations of mineral salts able to intensify this process (Andrade *et al.* 2017).

Plants that live in temporary ponds, such as *A. heterophylla,* tend to accommodate their life cycles to the duration of the hydroperiod of the environment (Cherry & Gough 2006). In the Caatinga, such ponds exhibit two distinct phases: a wet phase, which usually begins after a period of more intense rainfall, and a dry phase, which usually occurs shortly after the onset of the long dry season (see Andrade *et al.* 2017, for spatial variability in rainfall results in the Caatinga). Due to the ecological unpredictability of these environments, aquatic plants from temporary ponds presented a range of adaptations to periodic water loss and high survival resilience. Once the dry phase is overcome, the reestablishment of the population structure is possible largely thanks to long-lived seed banks (Brock *et al.* 2003), since the vegetative propagules are generally not resistant to the prolonged dry phase of ponds (Grillas *et* *al.* 1993). This feature is extremely important for the maintenance of aquatic plant populations in environments where the water balance is negative, as in the Caatinga.

In general, the results obtained by SDM show that the highest probabilities of presence of *A. heterophylla* are associated with annual rainfall of less than 1100 mm and high aridity (aridity index less than 0.6). Above these values, the average probability of presence dropped to less than 0.2 (Figure 1). Throughout the Caatinga, annual rainfall varies greatly in time and space. Most of the region (68.8%) receives between 600 and 1000 mm of rain per year, with high evapotranspiration rates that characterize the semiarid Caatinga climate (Sampaio 2010, Andrade *et al.* 2016). Although *A. heterophylla* is a rare-occurrence plant restricted to the margins of lakes or temporary ponds, the climatic conditions of its habitat are present in a large portion of the Caatinga area, when compared to the general bioclimatic characteristics of this biome. This enhances the predictive trust of our SDM by predicting 59.53% of the background extent as environmentally suitable.

The map obtained by SDM indicates high environmental suitability for three large regions (states of Rio Grande do Norte and Paraíba, states of Bahia and Pernambuco, and state of Ceará) that largely overlap the regions of the Brazilian semiarid where temporary ponds are more numerous (see Maltchik 2000). Generally occurring in an isolated way in space and presenting an ephemeral character (Campelo 2014), temporary ponds have been neglected for years (Williams 2006), and the result is that with little information, it becomes difficult to protect and conserve these environments and the species that live in them, such as *A. heterophylla*.

Although the current Brazilian PAs network has failed to protect most endemic species and evolutionary lineages (Oliveira *et al.* 2017), the record of populations of *A. heterophylla* in PAs and PACCs demonstrates the importance that these types of areas/units have for the maintenance of this species in natural ephemeral environments. Therefore, we recommend that collection efforts be undertaken at the five PAs and four PACCs indicated by the SDM as being of high environmental suitability (≥ 0.8) for the occurrence of *A. heterophylla* (Figure 2b). The obtaining of new records of *A. heterophylla* for the PAs or PACCs indicated by SDM can serve to support future actions regarding the selection of important areas for the conservation of biodiversity or valuation of those already in existence in the Caatinga.

However, it is important to emphasize that decision-making in the evaluation or selection of important areas for biodiversity conservation requires detailed and systematic assessments involving geoprocessing, landscape ecology and biogeography of as many species as possible (Whittaker *et al.* 2005), among other investigations of local scale, such as land use and occupation conflicts (Loyola & Lewinsohn 2009). Thus, any decision-making about PAs or PACCs based only on biogeographical aspects of a target species can be viewed as arbitrary and biased. Studies using SDMs are seen as fundamental in the initial stages of the process of selecting areas of high value for biodiversity conservation (Myers *et al.* 2000, Koch *et al.* 2017). Therefore, the results of the present study should only be seen to direct and supplement future systematic discussions regarding PAs and PACCs.

In summary, the distribution of *A. heterophylla* in the Caatinga was robustly predicted for three large areas of high environmental suitability with characteristics of high aridity and low annual precipitation. Here we explore the use of SDMs for species that are highly relevant to conservation biology (*A. heterophylla*, for example) and can be used to initially guide collection efforts and subsequently promote future discussions on PACCs and PAs from a systematic perspective. However, we point out that uncertainties associated with SDM forecasts may depend largely on the number of records used to run the model and/or the method of choice of the algorithm (Cunningham & Lindenmayer 2005, Proosdij *et al.* 2016). Therefore, we undoubtedly need exhaustive studies focused on aspects of species ecology, particularly endemic and rare species, which may have far-reaching implications for supporting more effective conservation actions.

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Supplementary Material 1. *Anamaria heterophylla* (Plantaginaceae). Details of the aquatic habit, heterophily, acrodrome venation and thirsoid inflorescence with ramifications in dicasio.

Supplementary Material 2. Records of *Anamaria heterophylla* accurate and without influence of spatial autocorrelation bias.

Supplementary Material 3. Eigenvales of the variables for the significant axes of PCA.

Supplementary Material 4. Correlation circle of the first two axes of the Principal Component Analysis.
Supplementary Material 5. Values of the contribution of the ten optimization procedures and the final average model.

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