Cereus jamacaru DC. and Pilosocereus pachycladus F. Ritter (Cactaceae) in the Northeast region of Brazil: future perspectives and distribution

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ABSTRACT
The Caatinga covers 912,529 km² throughout most of the Northeast region of Brazil and accounts for 28.6 million people. This region is characterized by high aridity and long drought periods. In 2013, the International Panel on Climate Change (IPCC) warned that tropical regions, including the semi-arid region of Brazil (mostly covered by Caatinga), will be affected by global climate change. Species of ecological and socio-cultural importance may be impacted by climate change, culminating in a local vulnerability scenario. Our goal was to elaborate maps to predict the future distribution of Cereus jamacaru DC. Subsp. Jamacaru and Pilosocereus pachycladus F. Ritter subsp. Pernambucoensis (F. Ritter) Zappi as a function of climatic changes. The results indicate that C. jamacaru will increase its distribution in 2050 (in the RCP8.5 scenario) while P. pachycladus will decrease in suitable habitat These findings reaffirm the prediction of desertification in the Caatinga. The interrelationship between man and the studied species, as plant resources, should also be considered to evaluate the social impact and vulnerability conditions of populations that depend on plant resources.

Keywords: Climate change, Cactaceae, Semi-arid Brazil, Caatinga.

Cereus jamacaru DC. E Pilosocereus pachycladus F. Ritter (Cactaceae) na região Nordeste do Brasil: perspectivas e distribuição futuras

RESUMO
A Caatinga ocupa 912.529 km² abrangendo grande parte da região nordeste do Brasil onde habitam 28.6 milhões de pessoas. Esta região é caracterizada por altas temperaturas e longos períodos de seca. Em 2013, o Painel Internacional sobre Mudanças Climáticas (IPCC) alertou que as regiões tropicais, incluindo a região semiárida do Brasil (principalmente a parte coberta pela Caatinga), serão afetadas pelas mudanças climáticas globais. Espécies de importância ecológica e sociocultural podem ser impactadas pelas mudanças climáticas, culminando em um cenário de vulnerabilidade local. Nosso objetivo foi elaborar mapas para prever a distribuição futura de Cereus jamacaru DC. subsp. jamacaru e Pilosocereus pachycladus F. Ritter subsp. Pernambucoensis (F. Ritter) Zappi em função das mudanças climáticas. Os resultados indicam que C. jamacaru aumentará sua distribuição em 2050 (no cenário RCP8.5) enquanto diminuirá habitat

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adequado para *P. pachycladus*. Esses achados reafirmam a previsão de desertificação na Caatinga. A inter-relação entre o homem e as espécies estudadas, como recursos vegetais, também deve ser considerada para avaliar o impacto social e as condições de vulnerabilidade das populações que dependem dos recursos vegetais. 

**Introduction**

The Caatinga covers most of the semi-arid region of Brazil. It occupies 80% of the Northeast Region and a small area in the Central-West Region (in Minas Gerais), an area that encompasses nine states. It has low annual average rainfall, high aridity indices, and the frequent occurrence of long drought periods, with rainy months from January to April and no rain from May to December (Prado, 2003; Moura et al., 2007). In Brazil, this region accounts for more than 28.6 million people who are distributed over 912,529 km² (Silva, 2011).

Low-tech agriculture, the main source of income for the majority of the population, combined with the dependence on natural resources due to the extreme climate, results in a scenario of socioeconomic vulnerability (Angelotti et al., 2011). A system is considered vulnerable when it is susceptible to climate events/changes, due to physical or social factors, and demonstrates an inability to adapt to the consequences of these changes (Adger et al., 2003). Understanding this concept is essential to interpret the impact of climate change on human populations (Adger and Kelly, 1999).

A report, published in 2013 (The Physical Science Basis) by the International Panel on Climate Change (IPCC), warned that tropical regions, including the semi-arid region of Brazil, will be affected by global climate change, with a consequent increase in temperature and a shorter time interval between drought periods, which will directly affect water resources (IPCC, 2013). Climate change directly affects the physiological dynamics and ability of plant species to remain in affected areas. Changes in atmospheric patterns on a large scale may increase the demand for evapotranspiration (Souza et al., 2015), which would cause water stress in plant species. This situation was recorded throughout the Atlantic Dipole phenomenon in the Caatinga in 2012 which prolonged the period of low precipitation (Gutiérrez et al., 2014). In this context, species distribution models based on climate change are widely used and may help to predict possible impacts on species distribution in areas exposed to climate change (Peterson et al., 2002; Thuiller, 2004; Araújo et al., 2006; Pearson et al., 2006; Thuiller et al., 2009).

Spatial distribution modeling has become common for two reasons: (1) access and advancement in statistical methods and instruments, which may use field surveys as well as data from museums and herbariums, and (2) the availability of environmental data at levels that can reproduce the distribution in any area of the world, making it possible to work on a global scale (Marco Júnior and Siqueira, 2009).

In the case of the Caatinga, distribution studies focused on specific botanical families, including Cactaceae, already attempted to relate their distribution to species diversity (Menezes et al., 2013) as well as altitudinal variation and nearby inhabited residences, such as precursor studies on domestication (Lucena et al., 2015a). These studies consider the ecological, cultural, and economic importance of this botanical family within the biome; however, studies that deal with the climatic factor and its influence on the distribution of species are still needed. From this perspective, Cactaceae is a highly representative botanical family in Northeast Brazil (Castro, 2008; Silva et al., 2017), because it has specific morphophysiological characteristics such as photosynthetic stems with a thick cuticle, no leaves, mucilaginous tissue, and water saving in processes used to obtain energy (Terrazas and Mauseth, 2002); it is well adapted to semi-arid environments. Thus, it became an abundant resource for diverse purposes, since it is available even in drought periods (Duque, 1980; Lucena et al., 2012, 2013, 2014, 2015b).

Lucena et al. (2015a) reported the importance of this family in a study performed in the state of Paraíba. They explained that the lack of native pasture combined with the water deficit leads small farmers to use native cacti species in an attempt to solve animal feed problems. This practice has been repeated for each drought cycle over the years (Duque, 2004; Cavalcanti Filho, 2010; Nunes et al., 2015).

*Cereus jamaicaru* DC. subsp. *jamaicaru* and *Pilosocereus pachycladus* F. Ritter subsp. *pennambucoensis* (F. Ritter) Zappi are the main species used as fodder in the semi-arid region of Brazil: they are columnar and tree-sized, widely found in this region, and used due to their utilitarian versatility and considerable numbers (Lucena et al., 2015a, 2015b; Dantas et al., 2017; Silva et al., 2019). Cactaceae species are important resources for use as fodder, food, in rural and domestic
constructions, in folk medicine, and as energy sources (firewood). The possible preference of farmers for the use of native species, especially *C. jamacaru* and *P. pachycladus*, is due to drought periods and consequent lack of pasture for the herds (Carvalho, 2016).

In this context, the present research is based on the hypothesis that the prediction of a reduction in the regular intervals of drought regime, combined with temperature increase, will influence the availability and distribution of native cactus species that are primarily used as fodder resources in periods of scarcity. Thus, this study aimed to elaborate current prediction maps of future *C. jamacaru* and *P. pachycladus* distributions, as a function of climatic changes, and to relate fodder use dynamics to the drought regime in the Caatinga and identify the consequences of climate change on these species.

**Material and methods**

Areas with known *C. jamacaru* and *P. pachycladus* occurrence, obtained from the Global Biodiversity Information Facility - GBIF (https://www.gbif.org), were also used (through functions with the spocc and mapdata packages in R software) in order to search for occurrence data and clean duplicate points. This procedure aimed to obtain the distribution of both species in the Northeast region and resulted in 130 *C. jamacaru* and 98 *P. pachycladus* specimens. From the two data collection modes, we obtained 255 *C. jamacaru* and 228 *P. pachycladus* distribution points used in the analyses.

We used a modeling database that consisted of 19 bioclimatic variables (Hijmans et al., 2005) and a biophysics variable (elevation) with a spatial resolution of 30 seconds of arc (approximately 1 km²) obtained from the WorldClim dataset (www.worldclim.org). Current climate data correspond to the interpolated database from 1960 to 1990. Observations of the representative scenarios of carbon dioxide concentrations (RCPs), optimistic (RCP4.5) and pessimistic (RCP8.5), as derived from the HadGEM2-ES model, allow one to formulate a predictive niche model that demonstrates the possible distribution of the species by the year 2050 (average predictions for 2041-2060). These data were the most recent climate projections of the Global Circulation Models (GCMs) used in the fifth IPCC report (CMIP5).

To reduce multicollinearity, highly correlated variables (Pearson’s correlation coefficient $r \geq 0.85$) were excluded (Graham, 2003). This reduction resulted in the inclusion of 12 predictor variables: isothermalism (Bio3), seasonality of temperature (Bio4), maximum temperature of the hottest month (Bio5), minimum temperature of the coldest month (Bio6), annual thermal amplitude (Bio7), average temperature of the wettest term (3 months) (Bio8), average temperature of the coldest term (Bio11), annual precipitation (Bio12), precipitation in the driest month (Bio14), seasonality of precipitation (Bio15), precipitation in the hottest term (Bio18), and precipitation in the coldest term (Bio19).

We used R software for ecological niche modeling using the MaxEnt (Phillips et al., 2006) through the dismo package (Hijmans et al., 2017). This algorithm has worked better with small samples in comparison to other modeling methods (Kumar and Stohlgren, 2009; Pearson et al., 2007). In the models of the present study, 75% of data for training and 25% for testing the model (Phillips and Dudik, 2008) were selected using k-fold partitioning, and 10,000 random background points were created. The Jackknife test was performed to determine the importance of the variables (Figure 1). The area under the curve (AUC) or receive operating characteristic (ROC) curve was used to evaluate the performance of the model. The AUC value ranges from 0 to 1 (Fielding and Bell, 1997). An AUC value up to 0.50 indicates that the model did not perform better than a random model, whereas an AUC equal to 1.0 indicates perfect discrimination (Swets, 1988).

For exhibition and later analysis, predicting the presence of a species (0-1), the models were reclassified with QGIS 2.18 (QGIS Development Team, 2018), based on a classification reference proposed by Yang et al., (2013) in five potential classes: unsuitable habitat (0–0.2); little suitable habitat (0.2–0.4); suitable habitat (0.4–0.6); highly suitable habitat (0.6–0.8); very highly suitable habitat (0.8–1.0) (Yang et al., 2013). The distribution area was calculated for each model, and binary values of presence (1) and absence (0) were obtained by using a cut threshold that maximizes the sum between sensitivity (true positives) and specificity (true negatives) according to the test data (MaxSS) (Jiménez-Valverde and Lobo, 2007; Liu et al., 2013).
Results

The current occurrence data (Figure 2) indicated changes in the probable distribution of the two species for both RCP4.5 and RCP8.5. For *C. jamacaru* (Figure 3A), the probability of its occurrence increased as the temperature increased. Since the scenarios simulate a higher carbon concentration, this species could be distributed in all Northeast region states, especially Piauí and Maranhão. For *P. pachycladus* (Figure 3B), there was a substantial decrease in the distribution probability for the RCP8.5 scenario, especially in Rio Grande do Norte, Paraíba, Pernambuco and Alagoas states.

The future distribution modeling (Figure 3) showed, to the detriment of climatic variables, an increase in highly suitable habitat (0.6–0.8) and very highly suitable habitat (0.8–1.0) to predict the presence of *C. jamacaru* (Figure 2A) in 2050, with a larger expansion in the RCP8.5 scenario. Conversely, there was an increase in unsuitable habitat (0–0.2) and a decrease in suitable habitat for the prediction of *P. pachycladus* presence (Figure 3B).

Figure 1: Evaluation of the relative importance of environmental variables by the Jackknife test. A and B show the results for *C. jamacaru* and *P. pachycladus*, respectively.

Figure 2: Current distribution map of *C. jamacaru* (A) and *P. pachycladus* (B). Notes: 1) species distribution points, 2) distribution according to the optimistic scenario (RCP4.5), and 3) distribution according to the pessimistic scenario (RCP8.5).
Figure 3: Future distribution map of C. jamacaru (A) and P. pachycladus (B). Notes: 1) species distribution points, 2) distribution according to the optimistic scenario (RCP4.5) and 3) distribution according to the pessimistic scenario (RCP8.5).

Discussion

The results from the predictive maps indicate a change in the distribution of the studied species, especially the expansion of areas with habitat favorable for C. jamacaru. This expansion may be related to the increase in areas undergoing desertification in the Caatinga biome. Future climate models and projections indicate a possible savannization in parts of the Amazon and intensification in the desertification process in the Caatinga as a consequence of the current global climate scenario (Torres et al., 2017). Such predictions would directly impact biodiversity, quality, and distribution of resources, as well as conditions for maintaining climate and life, such as water and carbon stocks.

The vulnerability to climatic variations of columnar cacti and other plants with a succulent stem may be explained as a relationship between the adaptive response of stem dimensions and precipitation variations in the environment where the plant is established (Williams et al., 2014). Therefore, when analyzing distribution data, the physiological characteristics of each species, and their ability to adapt to relevant climatic stress, should be examined. For this study, we considered that the climate abiotic factor will become the basis for future complementary studies that involve physiological and ecological aspects of the plants.

The semi-arid region of Brazil, according to global climate perspectives, will be one of the regions most affected by rainfall deficit and aridity increase (Marengo et al., 2017). These changes will directly impact human populations that live in this region and have an interrelationship with its natural resources. The social and cultural importance of the species under study result from this relationship between people and plant resources in the Caatinga. The use of C. jamacaru and P. pachycladus is one of the only alternatives for animal feed during drought periods in Paraíba communities (Lucena et al., 2015a).

Moreover, different review studies (Santos et al., 2017; Silva et al., 2019) that list documented uses of Cactaceae species, specifically C. jamacaru, emphasize the importance of its use by local populations in all northeastern states of Brazil and show that most of these uses are related to the feed security of herds during water scarcity periods. Silva et al. (2019) point out that it is necessary to invest in studies aimed at optimizing and prospecting the fodder potential of this species.

It is understood that climate change and its consequences directly affect the way of life of millions of people who live in the semi-arid region.
of Brazil. This directly impacts how these people relate to the environment and how they extract or conserve the natural resources essential for their survival. Thus, further studies on the use, management and conservation of Cactaceae should be carried out.

Therefore, the potential changes in *C. jamacaru* and *P. pachycladus* distributions may influence the dynamics of their use, local knowledge, and management by traditional populations. Thus, anthropogenic disturbance, which directly contributes to shortening natural climate cycles and consequent rapid advance in climate change worldwide (Torres et al., 2017), should be included in a complementary manner when interpreting data and climate prediction models, not only for causing degradation but as one of the factors for understanding the level of exposure and vulnerability of the ecosystem to these events.

There are some important and relevant questions for future scenarios: (1) Will the extraction and management of *C. jamacaru* and *P. pachycladus* be influenced by the increase/decrease in their availability or by the extreme climatic conditions? (2) Can these dynamics influence or trigger species domestication processes? (3) What are the ecological and cultural consequences of this new scenario? (4) What is the degree of socio-climatic vulnerability of these human populations to the detriment of the environmental changes that will occur?

Some of these answers have been sought in several regions of the world. Butt and Gallagher (2018) evaluate the vulnerability of plant species, considering their ability to adapt to climate change. Chombo et al. (2018) present an alternative for researchers who wishes to analyze the climate vulnerability of human populations in small regions. These studies may be theoretical instruments to be applied in the Northeast region of Brazil.

Ethnoscience studies direct the understanding of the relationship between the people and the environment, the use and management of species. The domestication process is closely linked to the use of morphological variability (Casas et al., 2016). Considering the importance of the documented Cactaceae columnar species, especially *C. jamacaru*, and the possible advance in the distribution, as well as the increased availability, it is essential to investigate how the dynamics of the relationship between local populations and this species will occur and the ecological and sociocultural characteristics of this interaction.

Some studies indicate it is still impossible to clearly state how Caatingan species will behave in the face of this new climatic scenario (Marengo et al., 2009; Marengo et al., 2017). Nevertheless, efforts in research should be allied with government initiatives that reduce poverty (and thus the dependence of rural populations on plant resources) while also aiming to reduce the pressure on native areas (Santos et al., 2014).

**Final considerations**

The data presented in this study indicate that the distribution and prediction of the occurrence of *C. jamacaru* and *P. pachycladus* will undergo changes in an extreme climate change scenario, a finding that reaffirms the predictions of desertification in the Caatinga.

The data obtained as a function of climatic variations (an abiotic factor) may contribute to in-depth studies involving the physiological adaptation capacity of species to climatic stress, as well as for the development of biodiversity management and conservation plans.

Plant resource extractions, as well as the interrelationship between man and the studied species, as plant resources, should also be considered to evaluate the social impact and vulnerability of the populations that depend on the resources, of which distribution will be altered over the years due to detrimental climate changes.

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