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Prediction of the natural distribution, habitat and conservation of *Stryphnodendron pulcherrimum* (Willd.) Hochr. in response to global climate change[1]

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ABSTRACT

Stryphnodendron pulcherrimum is a species used medicinally among traditional Amazonian communities for its bactericidal activity and anti-inflammatory properties. Despite being adapted to rustic environments, there is no information regarding how climate change might affect the species occurrence. The present study aimed to evaluate the natural distribution of *S. pulcherrimum* in the current period and how its potential geographic distribution may be affected in response to future climate change scenarios in Brazilian phytogeographic domains. A total of 19 bioclimatic variables were used from the WorldClim database. Four algorithm models (Climate Space Model, Envelope Score, Niche Mosaic and Environmental Distance - present) and one software (Open Modeller - future) were used to verify the potential occurrence of *S. pulcherrimum* in five Brazilian domains (Amazon, Cerrado, Caatinga, Atlantic Forest and Pantanal) and three intervals (2009-2019 - present; 2020-2050 and 2051-2070 - future). There were losses of areas favorable to the occurrence of *S. pulcherrimum* in the Amazon, Cerrado and Pantanal, and global climate change may affect its natural distribution especially in the Atlantic Forest and Amazon. In the Amazon, the species may be totally extinct, in the worst scenario, by 2070.

KEYWORDS: Medicinal plant, distribution of plant species, ecological niche modeling.

RESUMO

Predição da distribuição natural, habitat e conservação de *Stryphnodendron pulcherrimum* (Willd.) Hochr. frente às mudanças climáticas globais

Stryphnodendron pulcherrimum é uma espécie medicinal usada entre as comunidades tradicionais da Amazônia devido à sua atividade bactericida e propriedades anti-inflamatórias. Apesar de estar adaptada a ambientes rústicos, não há informações de como as mudanças climáticas poderão afetar a ocorrência da espécie. Objetivou-se avaliar a distribuição natural de *S. pulcherrimum* no período atual e como sua distribuição geográfica potencial poderá ser afetada diante de cenários de mudanças climáticas futuras nos domínios fitogeográficos brasileiros. Foram utilizadas 19 variáveis bioclimáticas a partir da base de dados do WorldClim. Quatro modelos de algoritmo (Climate Space Model, Envelope Score, Niche Mosaic e Enviromental Distance - presente) e um software (Open Modeller - futuro) foram utilizados para verificar a ocorrência potencial de *S. pulcherrimum* em cinco domínios (Amazônia, Cerrado, Caatinga, Mata Atlântica e Pantanal) e três períodos (2009-2019 - presente; 2020-2050 e 2051-2070 - futuro). Houve perdas de áreas favoráveis à ocorrência de *S. pulcherrimum* na Amazônia, Cerrado e Pantanal, e as mudanças climáticas globais poderão afetar sua distribuição natural especialmente na Mata Atlântica e Amazônia, sendo que, na Amazônia, a espécie pode estar totalmente extinta, no cenário mais pessimista, até 2070.

PALAVRAS-CHAVE: Planta medicinal, distribuição de espécies vegetais, modelagem de nicho ecológico.

INTRODUCTION

Increasing temperatures have caused extreme phenomena to occur more frequently. As a result, studies indicate that the Earth's temperature may rise about 5 ºC by 2100 (IPCC 2021). The concentration of gases, especially CO_2, is 40 % higher nowadays than in the pre-industrial era, due to fossil fuel consumption, amplifying the temperature effect (IPCC 2021).

The natural distribution of plant species is directly affected by climate change (McKenney & Pedlar 2003, Wang et al. 2016), due to significant increases in global mean temperatures and extreme weather events. Therefore, genetic variability acts both in the adaptation of species to dynamic environments and in their dispersal ability and ecological interactions (Soberón 2007, Desgroux et al. 2020). Studies to predict the current and future

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natural distribution of Brazilian tree species are necessary to counter the significant increase in global average temperatures and extreme climate events, due to the risk of reducing populations and their genetic variability (Souza-Moreira et al. 2018).

Stryphnodendron pulcherrimum is a pioneer species presenting disjuncture between areas of humid tropical forest and northeastern Brazilian States, with a center of occurrence in the Amazon (its largest distribution area) and Atlantic Forest (Gomes et al. 2021). It is also a medicinal species that exhibits antioxidant activity, for containing substantial concentrations of phenolic compounds (Lins Neto et al. 2016). It is used among quilombola communities to heal inflammation, cuts, wounds and bruises (Beltreschi et al. 2019). *S. pulcherrimum* also has a high potential in combating oral pathologies, for presenting tannins as the main class of biochemical compounds (Scalon 2007, Gomes et al. 2021).

Understanding the habitat preference of *S. pulcherrimum*, as well as the nature of anthropogenic threats, allows the development of indicators to assist in its proper management planning aimed at its conservation (Wrege et al. 2017, Tourne et al. 2019).

One of these tools is the Ecological Niche Modeling, which is successfully used to delimit the potential reach of the species (Sousa et al. 2020). Thus, this study aimed to evaluate the natural distribution of *S. pulcherrimum* in the current period and in future climate scenarios, using the Ecological Niche Modeling.

MATERIAL AND METHODS

Data for *Stryphnodendron pulcherrimum* were obtained by the Embrapa Florestas in 2021, from open access databases.

Geographic coordinates of consistent *S. pulcherrimum* occurrences were used from the survey of georeferencing points (latitude and longitude) from the SpeciesLink database (CRIA 2019). A total of 19 bioclimatic variables from the WorldClim (Hijmans et al. 2005), which generates maps with an approximate spatial resolution of 90 m and scale of 1:250,000, were used, as well as the main variables of importance for the distribution of the species, primarily air temperatures (minimum, maximum and average) and rainfall (Kumar & Stohlgren 2009). Data from the base period, or "present period", corresponded to 2009-2019, while future scenarios were projected for 2020-2050 and 2051-2070. In the generation of the basic climate layers used in the modeling process, multiple linear regression was used, relating the climate variables with the numerical models of latitude, longitude and altitude. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2021), the least pessimistic representative concentration pathways (RCP 4.5) and the most pessimistic (RCP 8.5) scenarios were determined. The least pessimistic scenario considered that preventive policies will be adopted to reduce greenhouse gases in the atmosphere, while the most pessimistic one considered that no strategies will be adopted to minimize the agents that cause the greenhouse effect.

Four algorithm models (Climate Space Model, Envelope Score, Niche Mosaic and Enviromental Distance) were used for the prediction of the species distribution, and the evaluation of the models was made by calculating the area under the curve (AUC) obtained from the integration of the receiver operating characteristic (ROC). The most representative model of the species distribution was selected based on the AUC curvature, where the maximum value of 1.0 indicates a perfect definition of the fitted models.

For modeling the prediction of the species occurrence, the Open Modeller software was used. Additionally, the maps generated from the algorithm models were transformed into numerical values ranging from 0 to 1, where 0 relates to no possibility of occurrence of the species and 1 corresponds to the maximum possibility of occurrence. A total of 980 georeferencing information points for the presence of *S. pulcherrimum* were reported in the SpeciesLink database (CRIA 2019) for the Brazilian territory, while some points were obtained from the Reflora virtual herbarium (Reflora 2021). The potential occurrence of *S. pulcherrimum* was verified for the current period in five Brazilian phytogeographic domains: Amazon, Cerrado, Caatinga, Atlantic Forest and Pantanal (Figure 1).

RESULTS AND DISCUSSION

The mapping of the current distribution of *S. pulcherrimum* was significant for all the models used ($p < 0.001$). The most representative model for the species distribution was selected based on the AUC, where a maximum value of 1.0 indicates a perfect discrimination of the adjusted models.

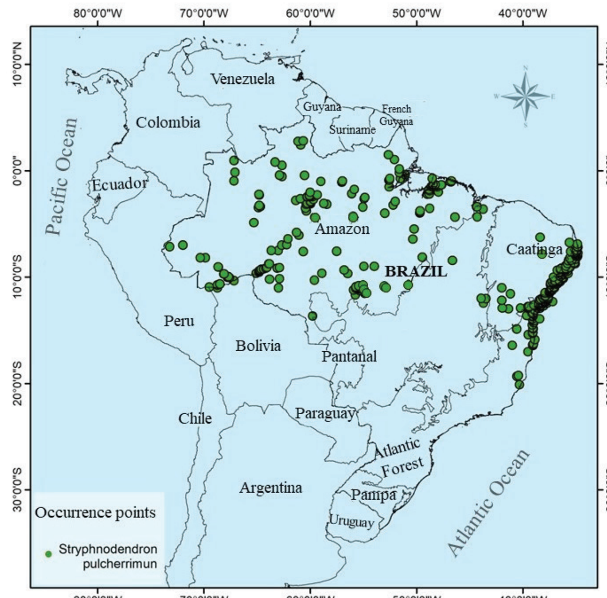

Figure 1. *Stryphnodendron pulcherrimum* occurrence data by phytogeographic domain in Brazil corresponding to the current period (2009-2019) (Environmental Distance model).

Figure 2. *Stryphnodendron pulcherrimum* distribution in Brazil by phytogeographic domain corresponding to the current period (2009-2019) (Environmental Distance model).

Accordingly, the Environmental Distance showed the highest similarity, regarding the distribution of the species, with the AUC considering the criterion of the maximum value of 1.0.

Although the species was found in the five most studied domains, there were more frequent occurrences in the Amazon and Cerrado (Figure 2). Considering that climate is a determinant factor in the variety of species at broad spatial scales (Figueiredo et al. 2018), it is noteworthy that the species has rusticity and does not have a good adaptation to the subtropical climate in Brazil.

The future projections for the scenarios RCP 4.5 (Figures 3 and 4) and RCP 8.5 (Figures 5 and 6) showed a reduction in areas favorable to the distribution of the species for 2020-2050 and 2051-2070, when all the domains present losses of suitable areas. The Amazon and Cerrado represent the most sensitive areas to the reduction of *S. pulcherrimum* populations.

According to the projections for 2020-2050 in the RCP 4.5 scenario, a loss of favorable areas is predicted to the development of *S. pulcherrimum* in the Amazon, Caatinga, Cerrado and Atlantic Forest, being more significant in the Amazon. In the future projection, the absence of suitable areas for the species in the Pantanal was verified (Figure 3). For 2051-2070, there are no records of significant favorable areas in the Amazon and Pantanal regions. In the Atlantic Forest and Caatinga, the occurrence may be slightly higher than in the Cerrado, where the species has already a low natural occurrence (Figure 3).

For the RCP 8.5 scenario, there is a significant loss of area for the species occurrence, with the Amazon, Cerrado and Pantanal being the most sensitive domains, and, for this reason, they are most affected by climate change. According to the projections for 2020-2050 in the RCP 8.5 scenario, there is no occurrence of favorable areas in the Amazon and Pantanal, with a lower occurrence in the Cerrado, Caatinga and Atlantic Forest (Figure 4). For 2051-2070, there is no species occurrence predicted for the Amazon, Cerrado and Pantanal (Figure 4). Notably, its occurrence in such distinct domains shows its rusticity and ability to adapt to different environments, a favorable situation for the implementation of conservation programs from these phytogeographic domains. The species present in the Caatinga and Atlantic Forest show a greater plasticity, even under a more persistent global climate change.

According to the occurrence maps (Figures 1 to 4), a significant reduction is predicted in the potential area for *S. pulcherrimum* in the coming decades, with the Amazon and Cerrado presenting a greater

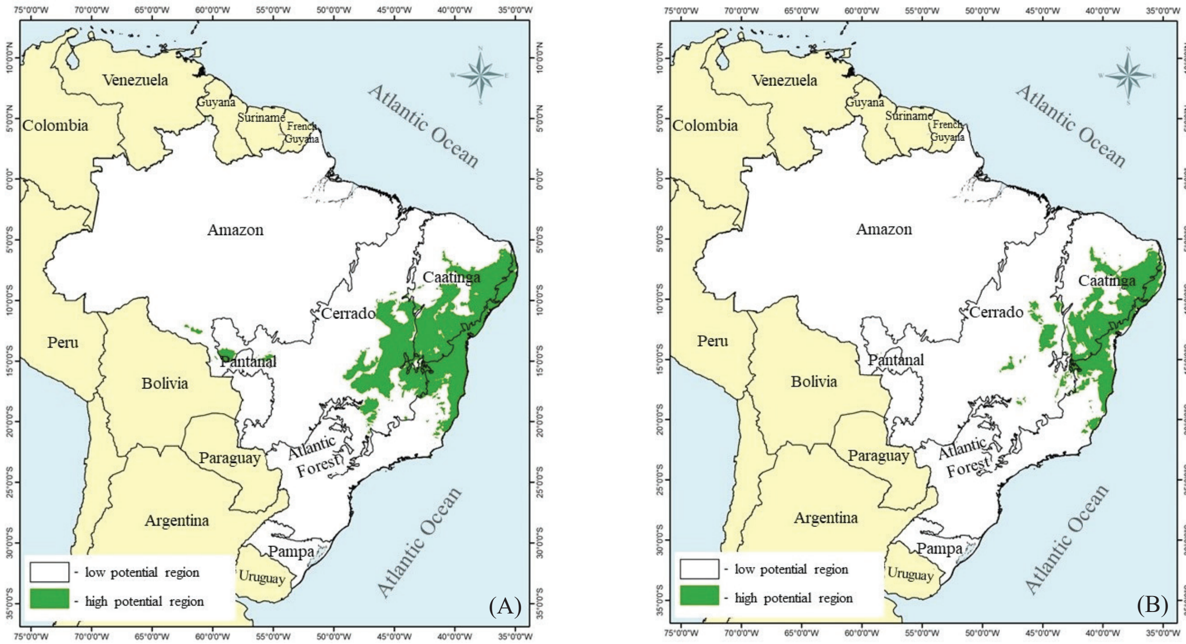

Figure 3. Projection for 2020-2050 (A) and 2051-2070 (B), in the less pessimistic scenario (RCP 4.5), of *Stryphnodendron pulcherrimum* distribution by phytogeographic domain, in Brazil, according to global climate change (Environmental Distance model).

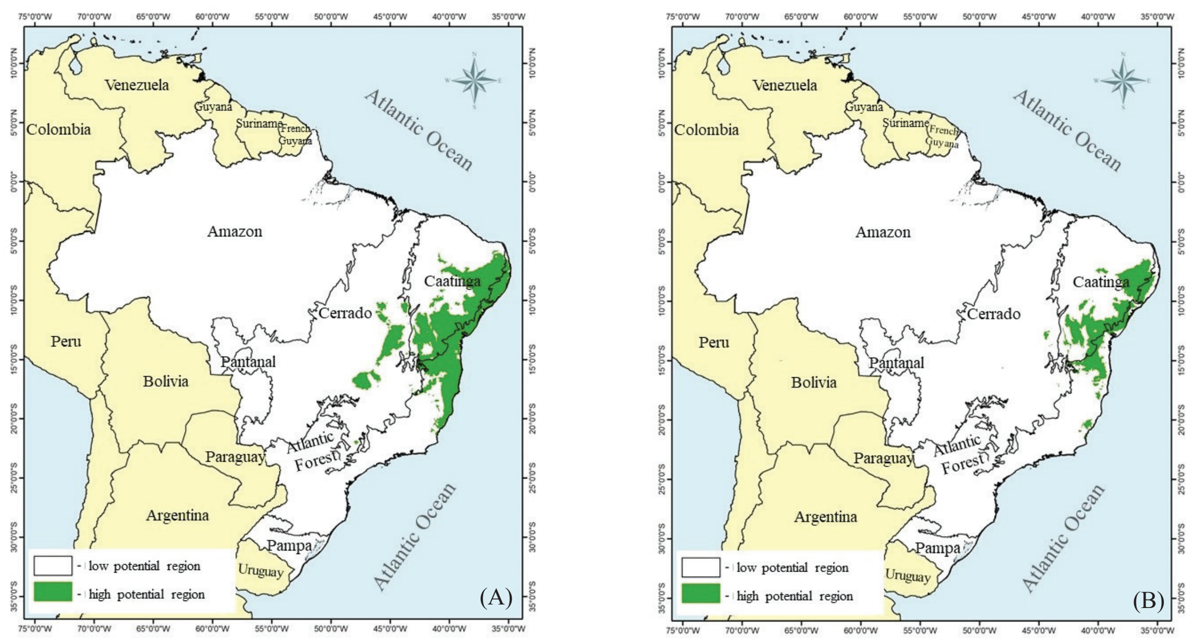

Figure 4. Projection for 2020-2050 (A) and 2051-2070 (B), in the most pessimistic scenario (RCP 8.5), of *Stryphnodendron pulcherrimum* distribution by phytogeographic domain, in Brazil, according to global climate change (Environmental Distance model).

potential for occurrence of the species in the current distribution. The change for 2020-2050 in the scenario RCP 4.5 shows an area reduction for the Pantanal, Amazon, Cerrado, Caatinga and Atlantic Forest (100, 99.81, 78.08, 50.99 and 41.29 %, respectively), with the Amazon and Cerrado standing out as the most affected in total area loss (4,206,266.77 and 1,732,127.06 km^2, respectively). For 2050-2070, this reduction may reach 100 % for the Amazon and Pantanal, 95.26 % for the Cerrado and 56.07 % for the Atlantic Forest (Table 1).

In the RCP 4.5 future climate scenario, from the current period, when compared to the 2051-2070 period, a smaller reduction in area loss is projected (6,745,974.68 km^2; Table 1), if compared to the RCP 8.5 scenario (7,024,074.58 km^2; Table 2).

Considering the RCP 8.5 scenario for 2020-2050, there was a reduction of 100 % in the favorable area for the Amazon and Pantanal, as well as 93.92, 46.79 and 22.29 % for the Cerrado, Atlantic Forest and Caatinga, respectively. For 2050-2070, there was an area reduction of approximately 100 % for the Cerrado, Amazon and Pantanal. For the Atlantic Forest and Caatinga, the reductions were 73.93 and 75.15 %, respectively (Table 2). According to the future projections made for the RCP 4.5 scenario, both for 2020-2050 and 2051-2070, an extinction of the species in the Amazon and Pantanal is verified, as well as a reduction of occurrence areas in the Caatinga, Cerrado and Atlantic Forest (Figure 5).

In the RCP 8.5 scenario, the Caatinga and Atlantic Forest presented *S. pulcherrimum* occurrence areas in 2020-2050 and 2051-2070 (Figure 6).

The species occurs both in environments with high (Amazon and Atlantic Forest) and low humidity (Caatinga and Cerrado) in the dry season, where there are areas of dense vegetation to large clearings, exposed soil or under thin cover (Schulz

Table 1. Projection area (km²), according to the less pessimistic scenario (RCP 4.5), for 2020-2050 and 2051-2070.

Phytogeographical domains	Current period (2009-2019)	2020-2050	Area loss (%)	2051-2070	Area loss (%)
Amazon	4,206,266.77	8,062.26	99.81	0	100.00
Caatinga	845,838.47	414,503.80	50.99	334,043.94	60.51
Cerrado	1,740,407.32	381,471.23	78.08	82,480.26	95.26
Atlantic Forest	439,097.33	257,780.15	41.29	192,915.64	56.07
Pantanal	123,804.63	0	100.00	0	100.00
Total	7,355,414.52	1,061,817.44	370.18	609,439.84	-

Table 2. Projection area (km²), according to the most pessimistic scenario (RCP 8.5), for 2020-2050 and 2051-2070.

Phytogeographical domains	Current period (2009-2019)	2020-2050	Area loss (%)	2051-2070	Area loss (%)
Amazon	4,206,266.77	0	100.00	0	100.00
Caatinga	845,838.47	657,319.73	22.29	210,213.48	75.15
Cerrado	1,740,407.32	105,887.52	93.92	6,655.02	99.62
Atlantic Forest	439,097.33	233,643.05	46.79	114,471.43	73.93
Pantanal	123,804.63	0	100.00	0	100.00
Total	7,355,414.52	996,850.30	362.99	331,339.94	-

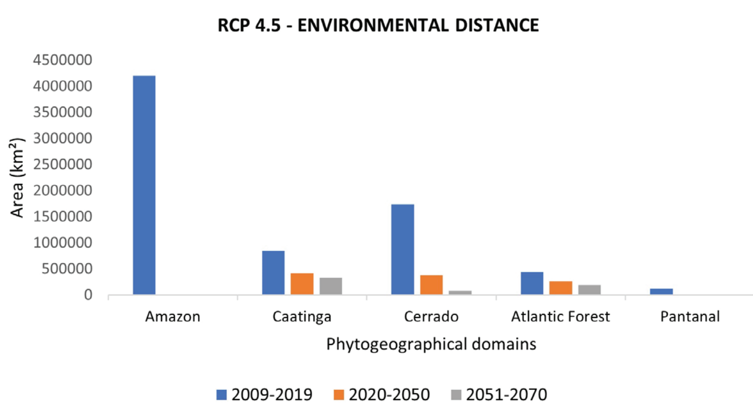

Figure 5. Distribution area (km²) by phytogeographic domain of *Stryphnodendron pulcherrimum* in the less pessimistic scenario (RCP 4.5) (Environmental Distance model).

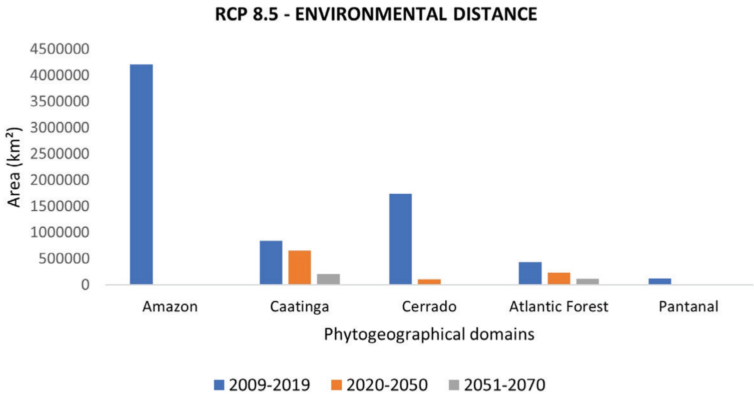

Figure 6. Distribution area (km²) by phytogeographic domain of *Stryphnodendron pulcherrimum* in the most pessimistic scenario (RCP 8.5) (Environmental Distance model).

et al. 2016). In general, the results suggest that *S. pulcherrimum* presents a wide plasticity, being tolerant to environments with high humidity and low water deficits, as is the case of the Northeast coast. According to Lorenzi (2008), its presence is common in environments in early stages of secondary succession, what suggests its suitability to various types of vegetal formation.

The distribution pattern of *S. pulcherrimum* was presented altered in future scenarios (RCP 4.5 and RCP 8.5) from 2051 to 2070 with climate change, as predicted for all the biodiversity (Parmesan & Yohe 2003, Thuiller 2007). The Amazon morphoclimatic domain, Cerrado and Pantanal demonstrated to be the most sensitive to the *S. pulcherrimum* occurrence in scenarios RCP 4.5 and RCP 8.5, for 2050-2070.

Although the Amazon is considered a species distribution center, it is among the most sensitive ecosystems to climate change (Seddon et al. 2016). In addition, it suffers intense predatory economic exploitation, much because of agricultural expansion and illegal logging (Campos et al. 2016), that may also contribute to advancing climate change. Since it already has high temperatures, this gradual increase is one of the determining factors in the reduction of biodiversity, because it causes losses to natural pollination, reproductive processes, germination, death of seedlings and developing plants. Additionally, climate change may also intensify dry periods in certain areas. Moreover, an increase in the length of the dry season for the southern Amazon region is predicted according to current hydrological trends and recent projections from global climate models (Boisier et al. 2015). Hence, the prediction of extinction in this domain for a rustic species such as *S. pulcherrimum* confirms a massive loss of species in the Amazon due to these changes (Feeley et al. 2012). Based on the most pessimistic predictions, there will be no favorable areas for the species to occur in this domain in the period of 2050-2070. A significant climate change in the Amazon is forecasted by the end of the 21st century, according to recent global climate model projections (Boisier et al. 2015), which predict to affect patterns of plant diversity (Olivares et al. 2015). In this way, to avoid extinction, species will need to track a propitious climate through migration or adapt to new climatic conditions.

Many Amazonian plant species are drought sensitive (Nepstad et al. 2007, Phillips et al. 2010), and with more severe dry seasons their ranges of occurrence may decrease (Feeley et al. 2012, Olivares et al. 2015). Observing the response of species as a function of annual rainfall, it is suggested that species in the region avoid dry conditions and tend to remain in tall, closed forests (Figueiredo et al. 2018), and more intense droughts result in the fragmentation of forests, making them more open (Hutyra et al. 2005, Olivares et al. 2015, Levine et al. 2016).

The generated models also indicate a fragility in the Cerrado domain, drastically decreasing areas favorable to the occurrence of the species in the most pessimistic scenario. The Cerrado is currently the main target of anthropogenic impacts, due to the expansion of the agricultural frontier (Nóbrega et al. 2020). Covering an area of over 2 million km², it is considered one of the most biologically diverse Savannas on the planet (Batlle-Bayer et al. 2010). However, due to its location, favorable climate and relief, it is considered a large agricultural field (Nunes et al. 2011). The Cerrado is rich in plant species that have medicinal potential (Ribeiro Neto et al. 2020), including species of the *Stryphnodendron* genus. Thus, it is possible to notice that *S. pulcherrimum* has a wide plasticity, adapting to the conditions of the more humid to the drier domains, since the species tends to decrease its distribution in the Atlantic Forest and Caatinga, but not being extinct.

The Caatinga vegetation, in turn, is quite heterogeneous (Schulz et al. 2016), but suffers a high degree of environmental degradation due to desertification processes (Santana et al. 2019). In addition, approximately 70 % of its original area have been altered, highlighting predatory logging and the replacement of vegetation cover for agricultural purposes and demographic expansion as the main factors of this alteration (Aguiar et al. 2016).

According to the Environmental Distance model, the Atlantic Forest showed a reduction in area of approximately 73.93 % in the RCP 8.5 scenario. This biome, according to Aguiar et al. (2016) and Bordonal et al. (2018), occupies 13 % of the Brazilian territory (1.1 million km²), and has been reduced to 193,000 km² due to the huge demographic expansion in the Southeast region. For that reason, 60 % are destined for planting, mainly sugarcane, coffee and soybean, what justifies the change of use of most of the area.

For the Pantanal, it was possible to verify that the species that occur in this area are restricted to the current period, with no region of high potential for the occurrence of the species in future scenarios. The Pantanal occupies an area of approximately 150,000 km² of the national territory. However, it is threatened mainly due to activities related to agricultural and mineral exploitation (Mello et al. 2015, Aguiar et al. 2016). Important microclimatic changes have been recorded for the Pantanal resultant of the conversion of forested areas to pasture, altering mainly the rainfall, temperature and energy balance regime (Biudes et al. 2012). Thus, any change in this system will reflect on the occurrence of the species, as is the case of S. *pulcherrimum* in future climate scenarios.

Climate change, by causing a reduction in the distribution of *S. pulcherrimum*, may reduce its genetic variability, what may intensify the inbreed mating in the species. The endogamy and effective populational size tend to influence the adaptation of forest species, especially in altered environments, making them more susceptible to disease and easily prone for extinction due to extreme climate change and habitat fragmentation (Brook et al. 2002, Kramer et al. 2008). Because of the predicted extinction of many species in the Amazon in future scenarios, it is pertinent to study native forest species to simulate the extreme conditions of climate change, such as seed germination at higher temperatures and planting under drought conditions. These studies may allow the selection of superior genotypes that are more resistant to these changes. The strategy can avoid adaptive losses for *S. pulcherrimum* and other species, because plants more competitive and tolerant to adverse conditions will be in the field in the reproductive stage.

Considering the socioeconomic and ethnobotanical importance of *S. pulcherrimum*, it is relevant that its genetic resources be characterized, so management and conservation strategies with the species can be more efficient. Studies that aim to assess the magnitude and distribution of genetic variability in these populations, along with how climate change will affect these factors in subpopulations, are essential for the conservation and use of the species. Natural populations of *S. pulcherrimum* located in the environments most vulnerable to global climate change should be prioritized for conservation, because environmental characteristics have a direct relationship with the species habitat and, consequently, the genetic variation distribution (Sousa et al. 2020). The effects of climate change, as well as habitat fragmentation due to anthropogenic impacts, lead to biodiversity loss and landscape disuniformity, thereby reducing dispersal success among populations and compromising the adaptive capacity of migrants, what may cause a decline in the species persistence, leading to local extinction in each scenery (With & King 1999, Fischer & Lindenmayer 2007). Therefore, the monitoring of *S. pulcherrimum* populations is suggested, especially in the most vulnerable ecosystems (Amazon, Cerrado and Pantanal).

CONCLUSIONS

Global climate changes may severely and significantly affect the entire natural range of *Stryphnodendron pulcherrimum*, especially in the Amazon and Atlantic Forest. In the Amazon, the species may become totally extinct, in the most pessimistic scenario, by the year 2070.

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