Climate change and local medical systems: future availability of medicinal plants for the treatment of climate-sensitive diseases

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Research

Abstract

Background: Climate change has intensified the incidence of climate-sensitive diseases (CSD) while simultaneously altering the availability of medicinal plant resources, with potential consequences for human health and the functioning of local medical systems (LMS), particularly in semiarid regions.

Methods: Species distribution models were developed for 83 woody medicinal plant species using occurrence records from GBIF and bioclimatic variables from WorldClim. Projections were generated for the year 2100 under current climatic conditions and three future scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) to assess changes in the availability of medicinal resources used in the treatment of dengue, chikungunya, zika, malaria, leishmaniasis, and yellow fever.

Results: Most species exhibited a contraction of suitable areas under future climate scenarios, with 68.7% showing consistent reductions across all projections. Losses were more pronounced among species associated with higher therapeutic diversity, and overall species richness declined markedly under the most extreme scenario (RCP 8.5).

Conclusions: Projected climate change is likely to reduce the availability of medicinal plant resources in the semiarid region, increasing the vulnerability of local medical systems by limiting therapeutic options for the treatment of climate-sensitive diseases.

Keywords: Arboviral diseases; Caatinga; Semiarid; Species distribution modeling

Background

Semiarid and hot arid regions occupy a considerable area of the globe and climate change is expected to cause increased warming, a reduction in relative atmospheric humidity and greater restrictions on water availability (Scholes 2020, IPCC 2023, Allen *et al.* 2024), with a projected increase in the incidence of climate-sensitive diseases (CSD), such as dengue, chikungunya, zika, malaria, leishmaniasis and yellow fever, which have epidemiological cycles modulated by climatic variables such as temperature, humidity and rainfall (McMichael 2003, Moreira *et al.* 2020, Romanello *et al.* 2023). In addition, the population contingent living in semiarid and arid regions is large, around 2.5 billion people, and the majority are economically vulnerable (Scholes 2020, Bouchaou *et al.* 2024) and highly dependent on forest resources, such as medicinal ones (Silva *et al.* 2017, Kumar & Rawat 2022), indicating that climate change may further increase the demand of human populations for therapeutic resources from forests.

Combined with the increased incidence of CSD, climate change may reduce the suitability of areas favorable to the occurrence of medicinal species, creating problems and challenges for public health. For example, some studies have indicated that the suitable areas for the occurrence of many species may be reduced or altered. In the Himalayas, areas favorable to the occurrence of some medicinal species may shift, concentrating in Nepal's mountainous regions (Kunwar *et al.* 2023). By the 2050s, a 39% net loss of habitat favorable to the occurrence of medicinal orchid species in India may occur (Kumar & Rawat 2022). In the Mediterranean, climate change combined with land-use patterns may reduce the diversity of aromatic medicinal plants and homogenize the biota (Kougioumoutzis *et al.* 2024). In semiarid regions of North Africa, some medicinal plants widely used by local populations will have their availability negatively impacted by climate change (Kachmar *et al.* 2021, El-Ghazouani *et al.* 2024, Radi *et al.* 2024). In South America, studies indicate that although some species benefit from climate change, most are likely to be negatively impacted, with reductions and fragmentation in their ranges (Silva *et al.* 2022, Alanis-Mendez *et al.* 2024). These findings are alarming because they alter ecological boundaries and the health of nature, generating impacts on human health (Mago *et al.* 2024, Redvers *et al.* 2025), especially by influencing the provision of medicinal resources used by local populations.

Although plants and animals in semiarid areas have evolved under conditions of water scarcity, presenting adaptive strategies that favor survival, the predicted changes in the variables temperature, relative humidity and water scarcity, combined with their interactions, can limit the productivity, richness, distribution and availability of organisms in forests, the production of secondary metabolites of medicinal importance, in addition to being able to modify the composition and content of secondary metabolites to reduce the effects of stresses caused by high temperature, reduced water availability and excess light, which can compromise the quality and efficiency of the medicinal use of the species (Thuiller *et al.* 2008, Foden *et al.* 2018, Pant *et al.* 2021, Cavalcante & Sampaio 2022, Exposito-Alonso 2023, Kougioumoutzis *et al.* 2024, Jangpangi *et al.* 2025). Furthermore, changes in the distribution, availability, quality, and accessibility of medicinal resources can alter the foraging behavior of human populations, leading to new learning about therapeutic resources and, possibly, cultural shifts. Consequently, it is challenging and extremely important to highlight the impact of climate change on services provided by biodiversity for human health (IPCC 2023, Romanello *et al.* 2023), which will also enable advances in projecting future changes in the functioning of local medical systems (LMS), such as changes in the availability of resources and therapeutic strategies, as well as their effects on the cultural transmission of medical knowledge (Ferreira-Júnior *et al.* 2015, Kumar & Rawat 2022, Dantas *et al.* 2024).

LMS are complex systems that express adaptive health care strategies based on traditional knowledge and the continuous use of forest resources, especially medicinal plants. These systems are complex because they reflect the characteristics of different ecological contexts, governance systems, and sociocultural factors that shape the adaptive strategies adopted (Kleinman 1978, Ferreira Júnior *et al.* 2015, Albuquerque *et al.* 2024). However, LMS demonstrate the importance of biodiversity services for the health of human populations, enabling the treatment of various diseases and contributing to the physical well-being of local populations, especially those with low purchasing power, who predominate in semiarid regions (Scholes 2020).

Species diversity and habitat availability strongly influence LMS by providing coverage of a broad spectrum of disease symptoms (Medeiros *et al.* 2020, Kougioumoutzis *et al.* 2024). Some LMS exhibit high functional redundancy because they are formed by different species with similar therapeutic uses, allowing the system to maintain its function even in the face of the loss or scarcity of a specific resource (Medeiros *et al.* 2012, Albuquerque *et al.* 2024). It is possible to perceive that functional redundancy in ethnobiological studies differs from the concept of ecological functional redundancy. According to Ferreira-Júnior et al. (2015), functional redundancy in ethnobiology refers to the number of species that share the same utilitarian function for human populations. In other words, functional redundancy in ethnobiology is a term used

synonymously with utilitarian redundancy, as it seeks to highlight the species that human populations use for the same purpose in different socio-ecological systems. Functional redundancy has been considered a key element of the resilience of LMS, enabling their reorganization and continuity in the face of environmental crises (Berkes & Turner 2006, Coe & Gaoue 2021). Consequently, functional redundancy favors the adaptive value of LMS for local populations facing environmental changes (Medeiros *et al.* 2020). However, some medicinal species have versatile uses (Reyes-García *et al.* 2013, Campos & Albuquerque 2021, Coe & Gaoue 2021, Mykhailenko *et al.* 2025), being collected and used by local populations for other non-medicinal purposes, which increases their use pressure. Therefore, if a resource with multiple functions in the system (i.e., with high use pressure) undergoes a reduction due to future climate change, its versatility may further exacerbate the decline in its availability to human populations. Thus, the reduction of versatile medicinal resources may decrease the resilience and adaptive value of LMS (Ferreira Júnior *et al.* 2015).

Few studies present an integrated analysis between epidemiological and ecological risks, whether due to loss or reduction in the availability of medicinal species, and assess the impact of these risks on traditional pharmacopoeia and public health. The predicted increase in CSD underscores the challenge and extreme relevance conducting an integrated analysis of climate-sensitive diseases, their symptoms, and the medicinal species that offer treatment. This remains unknown for different climate change scenarios, limiting our ability to: 1. assess the risks of health vulnerability of populations in semiarid regions; 2. identify future changes in the treatment of CSD and the foraging behavior of local populations; 3. assess the impact of climate change on the functionality and adaptive capacity of LMS in health care; and 4. identify strategies to mitigate the impact of climate change on public health.

In South America, semiarid regions occur in several countries, and in northeastern Brazil, they occupy almost the entire region, delimiting a geographic area known as the Caatinga region, which includes different types of vegetation, with a predominance of the largest seasonally dry tropical forest, locally also called the Caatinga (Araújo *et al.* 2007, Albuquerque *et al.* 2017, Antongiovanni *et al.* 2022). The Caatinga region exhibits high climatic and socioeconomic variability, and there are currently no studies assessing the joint effects of ecological and epidemiological risks. This region functions as a natural laboratory to observe the extreme effects of the climate crisis on local health systems.

The biocultural aspects of the LMS in the Caatinga region are diverse, reflecting the cultures of peoples of European, African, and Indigenous origin, as well as the characteristics of the socio-ecological systems. The region covers an area of 844,453 km² and currently houses more than 28 million people. Most residents of the rural areas engage in agricultural and livestock activities, have low purchasing power, limited access to schools and health centers, and a high dependence on vegetation resources such as firewood, timber, animal fodder, food, and medicinal plants. In some localities, local populations maintain the practice of cultivating and collecting medicinal and timber resources in their backyards, although they also collect directly from the forests or buy them in markets and open-air fairs. The socioeconomic characteristics of the populations in each area generally influence local knowledge about medicinal resources and their uses in the treatment of illnesses (Albuquerque *et al.* 2017, Silva *et al.* 2017, Farias *et al.* 2019, Campos & Albuquerque 2021, Medeiros *et al.* 2020, Sá-Filho *et al.* 2021, Souza *et al.* 2022).

Based on the above, this study compiles woody species currently known and used in the treatment of CSD, identifies the symptoms treated by each species to evidence the utilitarian redundancy of Local Medical Systems (LMS) related to CSD, and projects the species occurrence under three climate scenarios. Our hypothesis is that increased climate severity will negatively affect Local Medical Systems (LMS), reducing the availability of medicinal resources and, consequently, limiting the therapeutic alternatives for the treatment of CSD. If this limitation of therapeutic alternatives is confirmed, future climate scenarios may lead to a weakening of the protective role of functional redundancy in maintaining the resilience of LMS, not due to the number of species that treat the same symptom, but rather due to the reduction in the availability of medicinal resources. Thus, the study integrates ecological modeling, ethnobotanical knowledge, and functional analysis to highlight the health risks associated with biodiversity loss.

Materials and Methods

Selection of Species

The selected species were woody medicinal plants present in the Caatinga region of northeastern Brazil (Figure 1), including native and cultivated plants with documented use for the treatment of at least one symptom of diseases classified as CSD (Moreira *et al.* 2020). Woody species were selected because they do not exhibit seasonal occurrence, that is, they remain visible to human populations throughout the year (Albuquerque *et al.* 2017, Campos & Albuquerque 2021). Although many herbaceous species have medicinal value, they were not included because in the Caatinga region, most complete their entire

life cycle in the rainy season. In other words, they belong to the therophyte life form and become unavailable to local populations in the dry season, which can last from 6 to 9 months (Araújo *et al.* 2007, Aguiar *et al.* 2024).

The record of species use was based on the systematic review carried out by Campos and Albuquerque (2021), as this is the most recent work that compiled information from 75 studies on medicinal plants from the Caatinga region, bringing together 147 species (105 genera and 36 families) used in the treatment of symptoms of different diseases, including CSD with a high occurrence in the Caatinga region (Moreira *et al.* 2020), such as dengue (Aguiar *et al.* 2021, Carmo *et al.* 2020), chikungunya (Bartholomeeusen *et al.* 2023, Silva Junior *et al.* 2018), zika (Campos *et al.* 2018, Vissoci *et al.* 2018), malaria (Carlos *et al.* 2019, Griffing *et al.* 2015), leishmaniasis (Belo *et al.* 2023, Guimarães-Silva *et al.* 2023) and yellow fever (Cruz *et al.* 2023, Silva *et al.* 2020).

The indication of CSD symptoms was based on the literature: dengue (Endy *et al.* 2002, Rigau-Perez & Laufer 2006, Waterman & Gubler 1989), chikungunya (Das *et al.* 2010, Sergon *et al.* 2004), zika (Freitas *et al.* 2016, Petersen *et al.* 2016, Thomas *et al.* 2016), malaria (Alexandre *et al.* 2010, Couto *et al.* 2010), leishmaniasis (Badaró *et al.* 1986) and yellow fever (Monath 2001).

The symptoms were standardized in terms of nomenclature, taking into account the various clinical forms and terminologies found in the literature, using the Virtual Health Library of the Brazilian Ministry of Health as a reference. For example, the symptom joint pain can also be referred to as arthralgia or joint ache; all of these terms were unified under the name joint pain. This procedure aimed to consolidate the information and enable analysis of symptom associations across the studies consulted (Supplementary Material).

After standardizing the terminology, the symptoms were compared with the therapeutic uses attributed to the 147 species listed in the review by Campos and Albuquerque (2021), which allowed the identification and selection of 83 species (Table 1) used to treat at least one symptom of CSD. The number of species that treated each symptom was counted to evidence the utilitarian redundancy of the LMS. In addition, the number of symptoms treated by the same species was also counted to highlight the species that may face greater risks from climate change due to their versatility within the medical system. The occurrence data for the 83 species in different locations of the Caatinga region were extracted from the Global Biodiversity Information Facility (GBIF). Then, in R, the dataset was filtered to remove incorrect records, such as incomplete information, inconsistent coordinates, and duplicate records.

Species distribution modelling

The distribution modeling of the 83 selected medicinal species was performed for the Caatinga region (Figure 1), according to the official cartographic delimitation of the Brazilian Ministry of the Environment. The Caatinga region presents a diversity of environmental conditions that favor the occurrence of cerrado, Atlantic Forest, and seasonally dry tropical forest vegetation, the latter being predominant and locally designated as Caatinga (Araújo *et al.* 2007, Ferraz *et al.* 2004, Silva *et al.* 2019).

The models were designed for four climate predictions: one for the current scenario (year 2025) and three for the year 2100, based on the Representative Concentration Pathway (RCP) 2.6, 4.5, and 8.5. These scenarios, ratified by the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2023, Vuuren *et al.* 2011), simulate different trajectories of greenhouse gas concentrations and their associated climate impacts. The RCP 2.6 scenario predicts controlled emissions and a global temperature rise of around 2°C by 2100, with a probability of occurrence greater than 67%. RCP 4.5 projects a moderate temperature increase of around 3°C, with a probability above 50%. At the same time, RCP 8.5 represents a pessimistic scenario, with an increase above 4°C and a high probability (above 50%) of occurrence, due to continued emissions without effective control (IPCC 2023, Ordonez *et al.* 2024).

The climate data were obtained from the WorldClim database (v.1.4), which is widely used in species modeling studies due to its high precision of climate data (Hijmans *et al.* 2005). Considering a spatial resolution of 5 minutes (~9.3 km²), the bioclimatic variables used to model the distribution of the 83 species were: mean annual temperature (bio1), mean daily temperature range (bio2), isothermality (bio3), temperature seasonality (bio4), maximum temperature of the warmest month (bio5), minimum temperature of the coldest month (bio6), annual temperature range (bio7), mean temperature of the wettest quarter (bio8), mean temperature of the driest quarter (bio9), mean temperature of the warmest quarter (bio10), mean temperature of the coldest quarter (bio11), annual precipitation (bio12), precipitation of the wettest month (bio13), precipitation of the driest month (bio14) and precipitation seasonality (bio15).

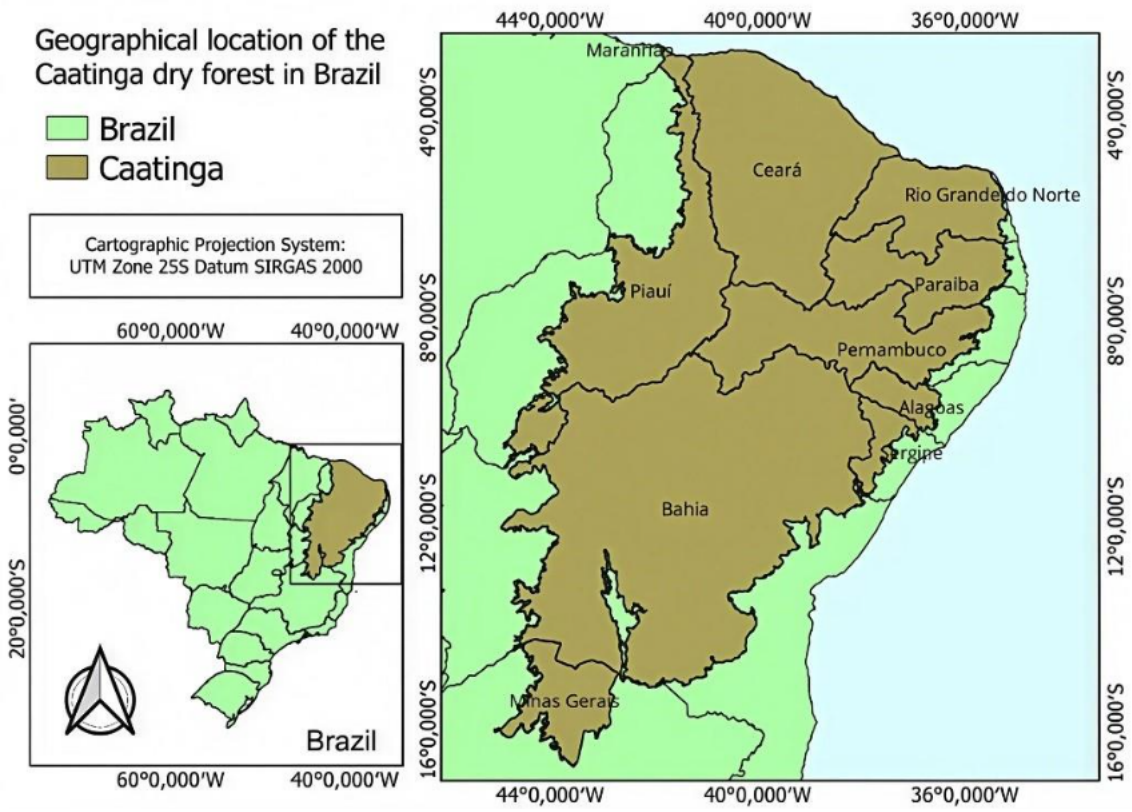

Figure 1. Map Location of the Caatinga region in northeastern Brazil. Shapefile Source: Ministry of the Environment (MMA).

Due to the characteristics of the set of bioclimatic variables used, the Random Forest (v.4.7.1.1) algorithm (Breiman 2001) was selected for modeling, as it presents greater accuracy in area under the curve (AUC) parameters when compared to other algorithms such as Bioclim, Domain, and MaxEnt (Luan *et al.* 2020). Modeling was performed in R using Machine Learning. To build the model, pseudo-absences were generated using the gRandom method, which creates records with locations based on the distribution of presences. For each of the 83 species, the data were split into training and validation sets, with 25% of the records reserved for independent performance evaluation. The average AUC for the 83 species was 0.85, indicating good predictive capacity of the species distribution models (SDM).

The climatic suitability of areas for each species' occurrence was calculated using the predict function of the 'dismo' (v. 1.3.14) package, and the threshold of 0.5 proposed by Monserud and Leemans (1992) was used to assess suitability. Areas with values greater than 0.5 on the probabilistic scale of the models for each projected scenario were considered favorable for the species' occurrence. In the projections, continuous probability values were converted to georeferenced binary matrices to identify suitable or unsuitable cells. The area of each cell corresponded to the spatial resolution of 5 minutes (~0.08333 degrees), equivalent to 9.3 km². The sum of all cells with a threshold value greater than 0.5 (Monserud & Leemans 1992) allowed us to calculate the extent of suitable occurrence for each species under the different climatic scenarios (current and RCPs 2.6, 4.5, and 8.5), expressed in km². Maps of future climate change scenarios are presented only for species exhibiting the greatest number of symptoms for each disease, as indicated by human populations (Campos & Albuquerque 2021).

Species Classification and Group Trends

The percentages of reduction, increase, or maintenance of the area favorable to species occurrence were calculated for each climate scenario, allowing classification of species according to the intensity of variation in their favorable areas. In this study, the favorable area for each species was classified into six categories, based on the intensity and direction of variation: strong (>65%), moderate (>30%-<65%), and slight (>0%-<30%), applied to both negative (decrease) and positive (increase) changes in area.

In addition, the tendency for future increase or decrease in the area occupied by the group of species used to treat each symptom was calculated. To calculate the group tendency, a numerical score (s) was assigned, ranging from 1 to 3, which

was positive when the category (Strong, Moderate, Slight) increased and negative when it decreased. The average score per symptom was calculated and converted to positive values by summing the maximum assigned scores (i.e., 3).

The average group tendency (T_MG) per symptom was calculated by the formula $T_MG = (ms + ps)/nc$, where *ms* represented the mean of the species, *ps* represented the maximum score assigned, and *nc* represented the maximum number of categories. This allowed standardizing the variation tendency on a scale of 0 to 1. The closer to 0, the greater the decreasing tendency, and vice versa. The average trend of the species group by symptom of each climate scenario was subjected to a quantile analysis to identify the cutoff points and visualize the average trend of species availability for the treatment of each symptom, resulting in the identification of 5 ranges of species availability: very robust (>0.8), robust ($\geq$ 60 $\leq$ 0.79), moderate ($\geq$ 0.4 $\leq$ 0.59), limited ($\geq$ 0.20 $\leq$ 0.39) and uncovered ($\leq$ 0.20).

Results

Increasing weather severity is projected to negatively affect the availability of woody medicinal plants used by local populations in the Caatinga region to treat climate-sensitive diseases (Table 1). Climate projections indicate that the areas currently occupied by several species, especially those with broader therapeutic uses, will tend to decline as climate scenarios become more severe (Figure 2), indicating that LMS will have fewer therapeutic alternatives for treating CSD.

All species persisted across all projected scenarios, but among the 83 species evaluated, 57 (68.7%) showed a consistent trend of decreasing area of occurrence across the three future climate scenarios (RCP 2.6, 4.5, and 8.5). Only eight species (9.6%) showed an increasing trend, and 18 (21.7%) exhibited a mixed trend, sometimes increasing and sometimes decreasing (Table 1). The reduction in area of occurrence was remarkably consistent among species that treated a greater number of symptoms, that is, with greater versatility in treating CSD symptoms. Of the 28 species associated with four or more symptoms, 16 (57.1%) showed a trend toward decreasing their area of occurrence, which is favorable to their occurrence (Figure 2), potentially compromising the functional breadth of therapeutic arrangements in LMS.

The climate scenario analysis revealed that the intensity of species range loss increases with climate severity. In RCP 2.6, although 68.7% of species will experience range decline, many will experience mild to moderate reductions. However, in RCP 4.5 and RCP 8.5 scenarios, the effects of climate change will be more significant, with species experiencing sharp reductions in range, such as *Croton odoratus* Baill., *Bauhinia forficata* Link, *Piper marginatum* Jacq., and *Ziziphus gardneriana* R.Br. in RCP 4.5 and, in addition, *Dioclea gardneriana* Benth., *Croton limae* Müll.Arg., and *Senna coronata* (Benth.) H.S.Irwin & Barneby in RCP 8.5. Therefore, the reductions observed in the modeling indicate that the progression of climate change will likely limit therapeutic options for treating CSD symptoms.

Some species may experience a significant increase in their range, such as *Croton sonderianus* Müll.Arg. in all projected scenarios, *Copernicia prunifera* (Mill.) H.E.Moore and *Tacinga gardneriana* (F.A.C.Weber) N.P.Taylor & Stuppy in scenario RCP 4.5, and *Guadua spinosa* Rupr. ex E.Fourn. in scenario RCP 8.5. However, all of them treat a small number (1 to 3) of symptoms (Figure 2). Therefore, the species that have increased in range (Figure 2; Table 1) have little diversity in their importance for the treatment of CSD in local medical systems, and perhaps this low versatility in treating symptoms does not compensate for the range losses recorded for most species that treat many symptoms.

The reduction in favorable areas for species occurrence indicated that some symptoms may or may not be amenable to treatment using medicinal plants (Figure 3). For example, in RCP 2.6, the robust trend of increasing the favorable area of the set of species that treat muscle pain will be very limited in RCP 8.5. The very robust trend of the set of species that treat itching will fall to moderate in RCP 8.5. Some symptoms will not show a change in the favorable area trend of the set of species used in their treatment, such as fever, whose set of species shows a robust trend; joint pain, a moderate trend; and headache, a minimal trend, across all climate scenarios.

Other symptoms may benefit from climate change, as the species that treat them tend to expand their favorable areas for occurrence, such as dehydration and liver disorders. The symptoms with the richest set of species for treatment in the current scenario are cough (37) and diarrhea (34), which occur only in leishmaniasis. In contrast, the symptoms with the lowest number of species for treatment are joint pain (1), which occurs in dengue, zika and chikungunya, and kidney problems (1), which occurs only in yellow fever and should have greater limitations for treatment, as the tendency of areas for the occurrence of the species is to become very limited from the RCP 4.5 scenario (Figure 3).

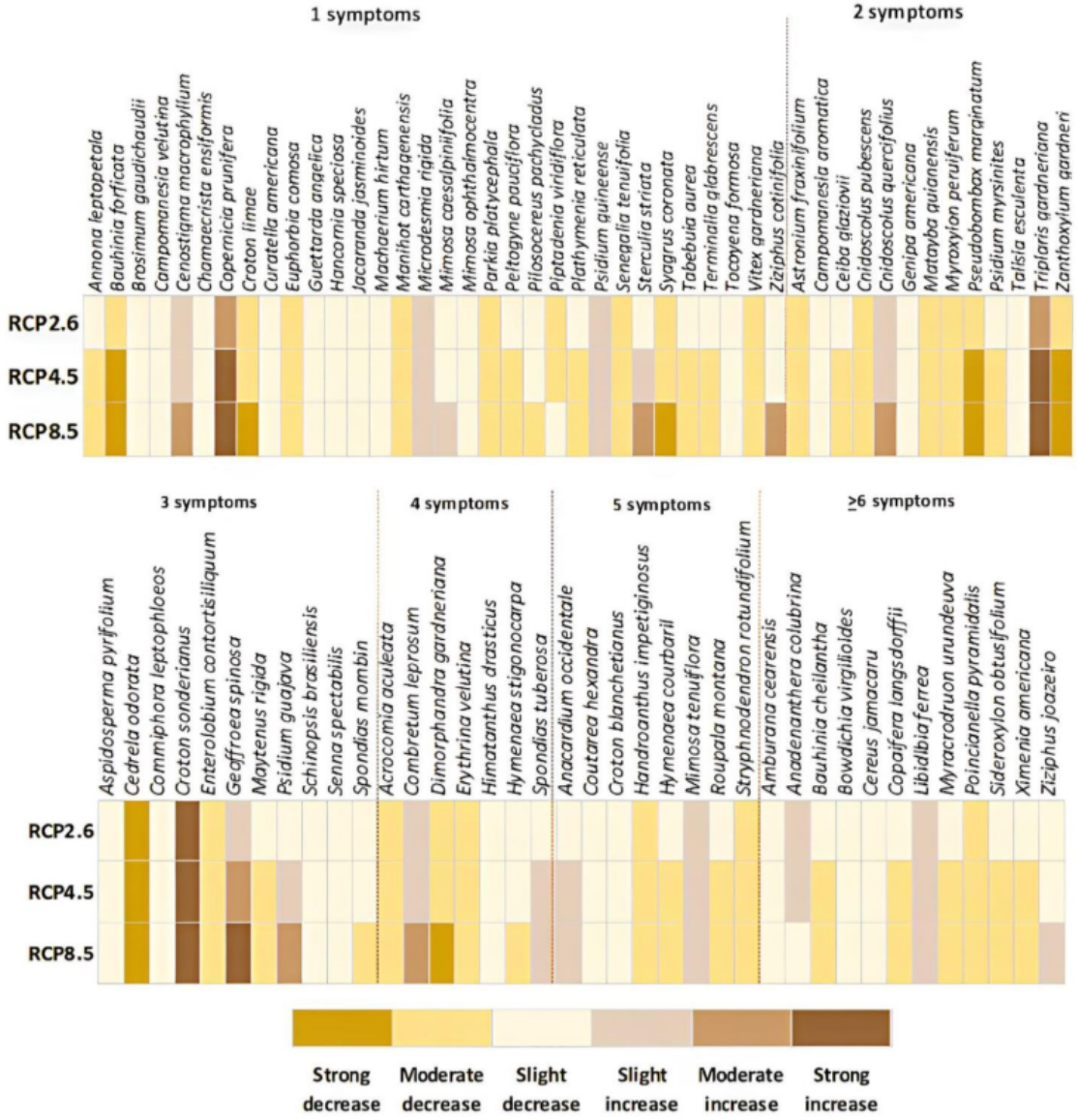

Figure 2. Intensity of change in the occurrence area of species used to treat symptoms of climate-sensitive diseases (CSD) under future climate scenarios (RCP 2.6, 4.5, and 8.5), organized by the number of symptoms treated by each species.

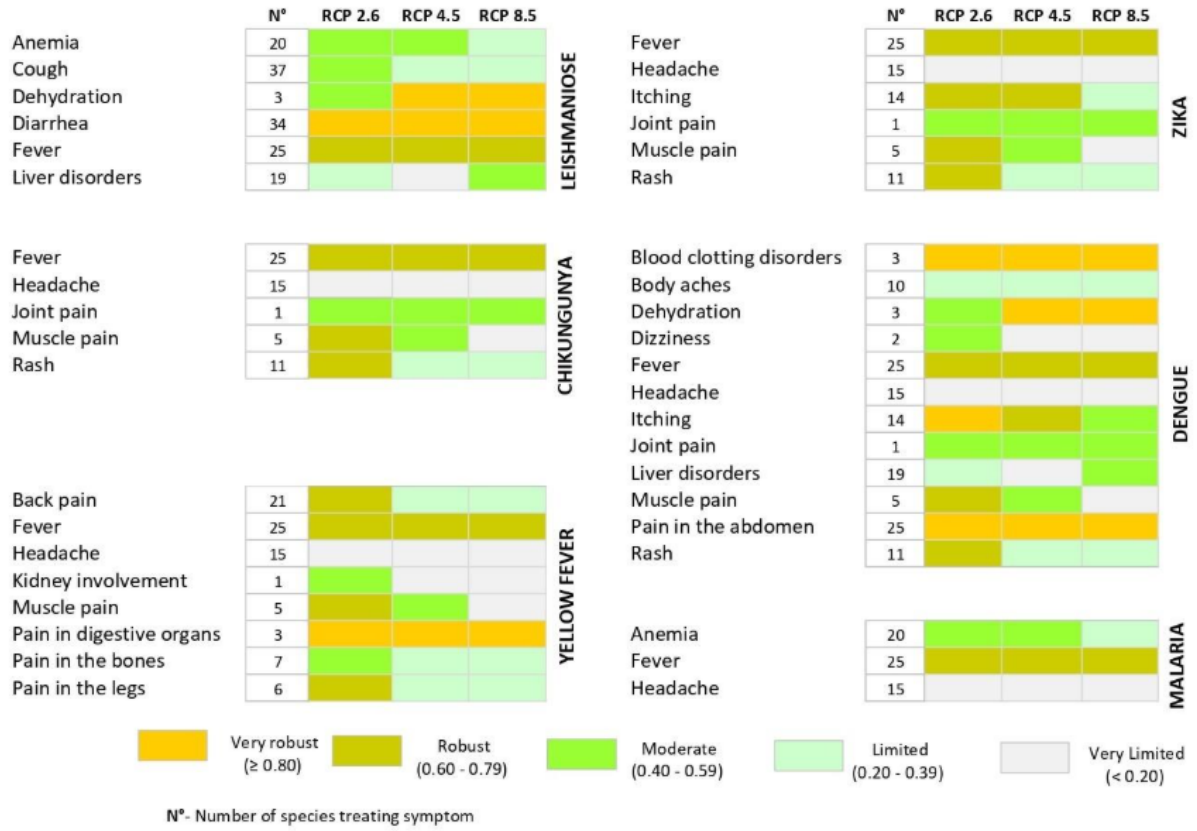

Figure 3. Species set treating symptoms, climate-sensitive diseases (CSD), and trends in the favorable occurrence area under the RCP 2.6, 4.5, and 8.5 climate scenarios.

The species that treats the highest number of symptoms in the CSD set is *Myracrodruon urundeuva* Allemão. However, it is not the most important species for treating each symptom in isolation, since the association between symptom type (Figure 2) and the species used in their treatment, as indicated by local populations (Table 1), revealed that the most important species in the Caatinga region for the treatment of dengue, zika, and chikungunya is *Amburana cearensis* (Allemão) A.C.Sm., treating 9, 6, and 5 symptoms, respectively. *Bowdichia virgilioides* Kunth, *Libidibia ferrea* (Mart. ex Tul.) L.P.Queiroz, and *Myracrodruon urundeuva* Allemão are equally important for the treatment of yellow fever, as they address five of its symptoms. *Anacardium occidentale* L., *Hymenaea courbaril* L., *Myracrodruon urundeuva* Allemão, and *Ximenia americana* L. treat three symptoms of malaria. Finally, *Libidibia ferrea* (Mart. ex Tul.) L.P.Queiroz, *Myracrodruon urundeuva* Allemão, *Ximenia americana* L., and *Ziziphus joazeiro* Mart. treat five symptoms of leishmaniasis (Table 1). The distributional projections indicated that there should be little change in the spatial location of the patches of areas most favorable for the occurrence of species that treat the highest number of symptoms for each disease (Figure 4 and Figure 5).

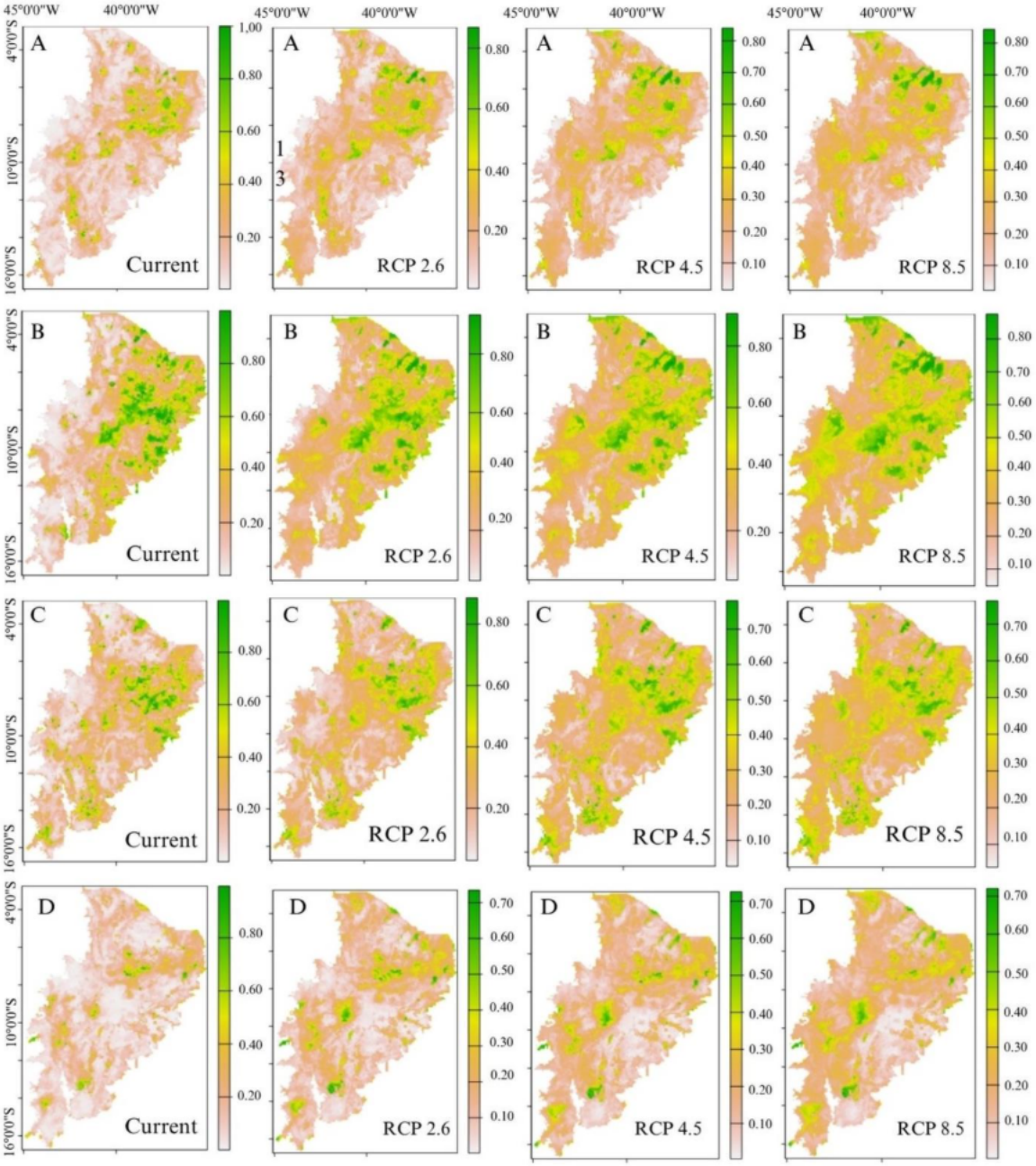

Figure 4. Spatial visualization of suitable areas for the occurrence of species that treat the most significant number of climate-sensitive diseases (CSD) in the Caatinga region projected under the Current, RCP 2.6, RCP 4.5, and RCP 8.5 scenarios (A = *Amburana cearensis*; B = *Libidibia ferrea*; C = *Myracrodruon urundeuva*; D = *Ximenia americana).*

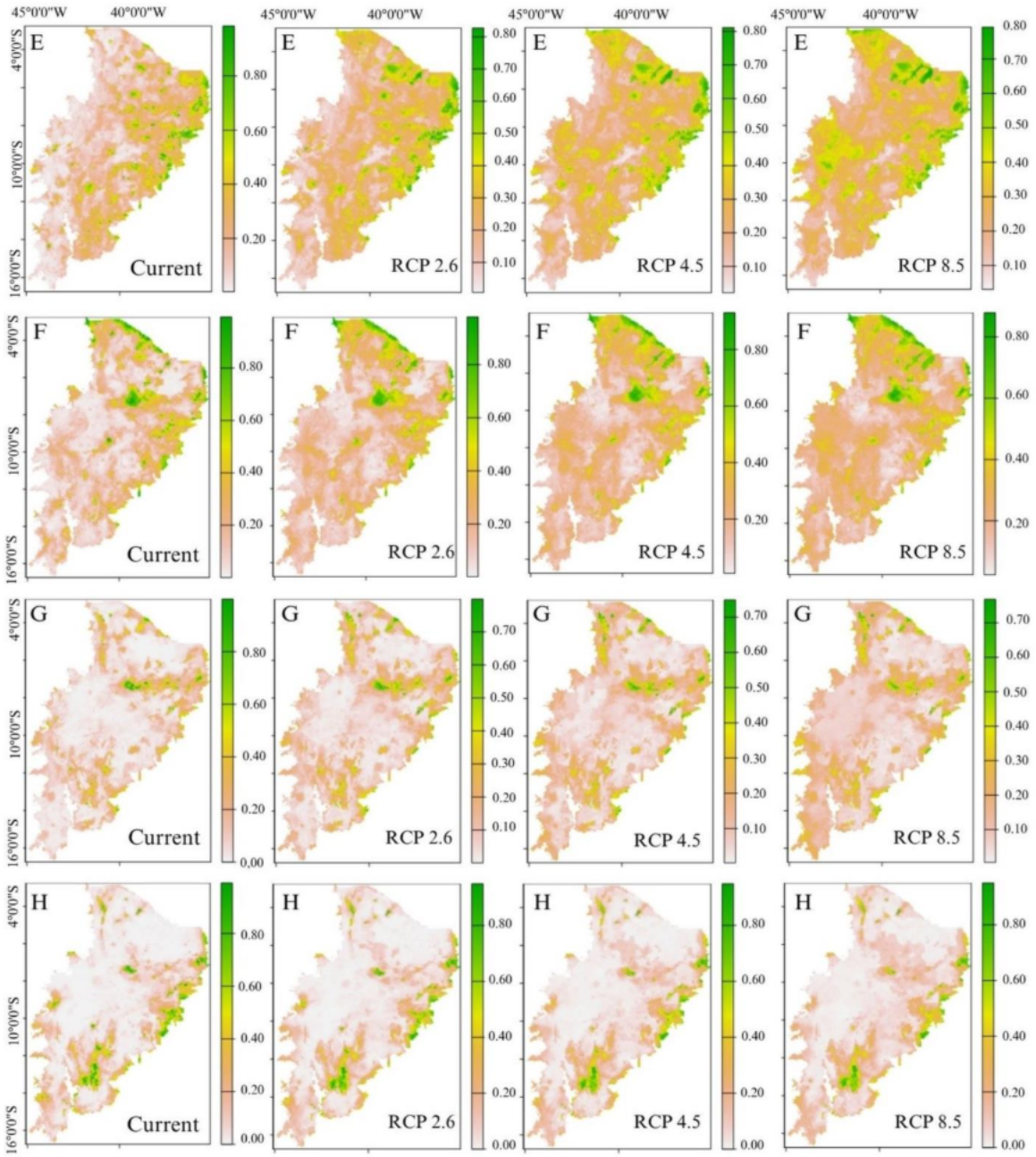

Figure 5. Spatial visualization of suitable areas for the occurrence of species that treat the most significant number of climate-sensitive diseases (CSD) in the Caatinga region projected under the Current, RCP 2.6, RCP 4.5, and RCP 8.5 scenarios. (E = *Ziziphus joazeiro*; F = *Anacardium occidentale*; G = *Hymenaea courbaril*; H = *Bowdichia virgilioides)*.

Table 1. Projections of area extension (Km²) favorable for the occurrence of woody species used in the treatment of climate-sensitive diseases (CSD) in the Caatinga region and percentage differences in relation to the current scenario (S = number of symptoms treated; AUC = Model accuracy; RCP = Representative Concentration Pathway).

			CLIMATE SCENARIOS						
			CURRENT	RCP 2.6		RCP 4.5		RCP 8.5	
SPECIES	NUMBER OF CSD SYMPTOMS TREATED	AUC	Km²	Km²	%	Km²	%	Km²	%
Acrocomia aculeata (Jacq.) Lodd. ex Mart.	4 (fever, anemia, cough, itching)	0.88	176.7	93	-47.37	74.4	-57.89	74.4	-57.89
Amburana cearensis (Allemão) AC Sm.	12 (fever, itching, headache, skin rash, muscle aches, dizziness, dehydration, joint pain, cough, stomach pain, diarrhea, back pain)	0.82	8081.7	7356.3	-8.98	7477.2	-7.48	7924	-1.96
Anacardium occidentale L.	5 (fever, anemia, headache, cough, stomach pain)	0.86	7616.7	7495.8	-1.59	7802.7	2.44	8165	7.20
Anadenanthera colubrina (Vell.) Brenan	8 (fever, anemia, itching, diarrhea, muscle aches, cough, stomach pain, back pain)	0.75	31025	31202	0.57	31117.8	0.30	30430	-1.92
Annona leptopetala (RE Fr.) H. Rainer	1 (anemia)	0.89	9272.1	7319.1	-21.06	6268.2	-32.40	5320	-42.63
Aspidosperma pyrifolium Mart.	3 (fever, diarrhea, stomach pain)	0.80	26998	25780	-4.51	25063.5	-7.17	24217	-10:30
Astronium fraxinifolium Schott	2 (fever, cough)	0.71	697.5	316.2	-54.67	269.7	-61.33	251.1	-64.00
Bauhinia cheilantha (Bong.) Steud.	6 (diarrhea, headache, cough, stomachache, back pain, bone pain)	0.84	13215	10221	-22.66	8695.5	-34.20	7180	-45.67
Bauhinia forficata Link	1 (itching)	0.83	465	223.2	-52.00	158.1	-66.00	130.2	-72.00
Bowdichia virgilioides Kunth	9 (fever, rash, cough, body aches, stomachache, back pain, leg pain, bone pain, headache)	0.88	7774.8	7021.5	-9.69	6798.3	-12.56	6705	-13.76
Brosimum gaudichaudii Trecul	1 (liver disorders)	0.87	1999.5	1915.8	-4.19	1869.3	-6.51	1869	-6.51
Campomanesia aromatica (Aubl.) Griseb.	2 (fever, cough)	0.90	2362.2	2139	-9.45	2101.8	-11.02	2120	-10.24
Campomanesia velutina (Cambess.) O. Berg	1 (itching)	0.96	381.3	344.1	-9.76	362.7	-4.88	372	-2.44
Cedrela odorata L.	3 (fever, headache, liver disorders)	0.82	437.1	93	-78.72	65.1	-85.11	18.6	-95.74
Ceiba glaziovii (Kuntze) K. Schum.	2 (anemia, back pain)	0.84	4947.6	3664.2	-25.94	3403.8	-31.20	3116	-37.03
Cenostigma macrophyllum Tul.	1 (fever)	0.90	4743	5645.1	19.02	5784.6	21.96	6175	30.20
Cereus jamacaru DC.	6 (fever, diarrhea, skin rash, liver disorders, cough, stomach pain, bone pain)	0.81	13522	12006	-11.21	12266.7	-9.28	12871	-4.81
Chamaecrista ensiformis (Vell.) HS Irwin & Barneby	1 (anemia)	0.99	465	399.9	-14.00	437.1	-6.00	427.8	-8.00

Cnidoscolus pubescens Pohl	2 (liver disorders, cough)	0.86	1571.7	725.4	-53.85	716.1	-54.44	678.9	-56.80
Cnidoscolus Quercifolius Pohl	2 (liver disorders, back pain)	0.89	10937	11820	8.08	12861.9	17.60	14666	34.10
Combretum leprosum Mart.	4 (fever, high fever, diarrhea, headache, stomachache, cough)	0.88	9569.7	11151	16.52	11997	25.36	12713	32.85
Commiphora leptophloeos (Mart.) JB Gillett	3 (fever, stomachache, cough)	0.81	16796	15010	-10.63	14424.3	-14.12	14062	-16.28
Copaifera langsdorffii Desf.	8 (fever, headache, rash, dizziness, cough, body aches, stomachache, back pain)	0.88	4082.7	3320.1	-18.68	2836.5	-30.52	2660	-34.85
Copernicia prunifera (Mill.) HE Moore	1 (itching)	0.96	2948.1	4082.7	38.49	5087.1	72.56	5803	96.85
Coutarea hexandra (Jacq.) K. Schum.	6 (fever, high fever, diarrhea, headache, stomachache, cough)	0.84	8528.1	7272.6	-14.72	6547.2	-23.23	5971	-29.99
Croton blanchetianus Baill.	5 (diarrhea, liver disorders, clotting disorders, cough, stomach pain)	0.87	18247	17614	-3.47	17567.7	-3.72	17465	-4.28
Croton limae AP Gomes, MF Sales & PE Berry	1 (liver disorders)	0.86	1181.1	641.7	-45.67	502.2	-57.48	362.7	-69.29
Croton sonderianus Müll. Arg.	3 (diarrhea, clotting disorders, stomach pain)	0.76	1488	3143.4	111.25	4240.8	185.00	5561	273.75
Curatella americana L.	1 (fever)	0.85	2343.6	2046	-12.70	1999.5	-14.68	1925	-17.86
Dimorphandra gardneriana Tul.	4 (diarrhea, cough, body aches, back pain)	0.84	744	344.1	-53.75	279	-62.50	241.8	-67.50
Enterolobium contortisiliquum (Vell.) Morong	3 (muscle pain, body ache, back pain)	0.84	3199.2	1720.5	-46.22	1646.1	-48.55	2027	-36.63
Erythrina velutina Willd.	4 (diarrhea, fever, headache, cough)	0.76	6640.2	4026.9	-39.36	3236.4	-51.26	2930	-55.88
Euphorbia comosa Vell.	1 (diarrhea)	0.86	5552.1	3413.1	-38.53	2873.7	-48.24	2316	-58.29
Genipa americana L.	2 (anemia, leg pain)	0.78	1581	1450.8	-8.24	1460.1	-7.65	1442	-8.82
Geoffroea spinosa Jacq.	3 (fever, anemia, diarrhea)	0.90	883.5	883.5	0.00	1339.2	51.58	2158	144.21
Guettarda Angelica Mart. ex Müll. Arg.	1 (fever)	0.82	7123.8	5598.6	-21.41	5384.7	-24.41	5227	-26.63
Hancornia speciosa Gomes	1 (diarrhea)	0.85	1636.8	1469.4	-10.23	1311.3	-19.89	1209	-26.14
Handroanthus impetiginosus (Mart. ex DC.) Mattos	5 (anemia, itching, body aches, back pain, bone pain)	0.80	8928	5226.6	-41.46	4185	-53.13	3869	-56.67
Himatanthus drasticus (Mart.) Plumel	4 (anemia, liver disorders, cough, stomach pain)	0.93	3366.6	3050.4	-9.39	3189.9	-5.25	3209	-4.70
Hymenaea courbaril L.	5 (anemia, headache, cough, bone pain, fever)	0.87	3348	2427.3	-27.50	2101.8	-37.22	1739	-48.06
Hymenaea stigonocarpa Mart. ex Hayne	4 (anemia, itching, cough, body aches)	0.95	2827.2	2176.2	-23.03	2018.1	-28.62	1683	-40.46
Jacaranda jasminoides (Thunb.) Sandwith	1 (itching)	0.87	3031.8	2697	-11.04	2687.7	-11:35	2613	-13.80

Libidibia ferrea (Mart. ex Tul.) LP Queiroz	12 (fever, high fever, anemia, diarrhea, liver disorders, leg pain, bone pain, back pain, stomach pain, pain in digestive organs, cough, itching)	0.78	20655	20795	0.68	21157.5	2.43	22246	7.70
Machaerium hirtum (Vell.) Stellfeld	1 (diarrhea)	0.90	3431.7	2752.8	-19.78	2557.5	-25.47	2492	-27.37
Manihot carthagenensis (Jacq.) Müll. Arg.	1 (diarrhea)	0.81	9755.7	6472.8	-33.65	5273.1	-45.95	4083	-58.15
Matayba guianensis Aubl.	2 (back pain, leg pain)	0.95	1004.4	688.2	-31.48	539.4	-46.30	446.4	-55.56
Maytenus rigida Mart.	3 (liver disorders, cough, body aches)	0.87	4966.2	3813	-23.22	3320.1	-33.15	3209	-35.39
Microdesmia rigida (Benth.) Sothers & Prance	1 (diarrhea)	0.94	2771.4	3348	20.81	3543.3	27.85	3571	28.86
Mimosa caesalpiniifolia Benth.	1 (liver disorders)	0.80	3747.9	3320.1	-11.41	3534	-5.71	4176	11.41
Mimosa ophthalmocentra Mart. ex Benth.	1 (skin irritation)	0.83	9969.6	8853.6	-11.19	8528.1	-14.46	8221	-17.54
Mimosa tenuiflora (Willd.) Poir.	5 (fever, diarrhea, skin rash, cough, stomach pain)	0.84	21613	21995	1.76	22887.3	5.90	24366	12.74
Myracrodruon urundeuva German	13 (fever, anemia, itching, diarrhea, headache, skin irritation, liver disorders, cough, body ache, back pain, leg pain, stomach pain, pain in digestive organs)	0.76	14229	10509	-26.14	8788.5	-38.24	7282	-48.82
Myroxylon peruiferum Lf.	2 (liver disorders, back pain)	0.93	102.3	65.1	-36.36	46.5	-54.55	37.2	-63.64
Parkia platycephala Benth.	liver disorders, back pain	0.96	1181.1	762.6	-35.43	716.1	-39.37	632.4	-46.46
Peltogyne pauciflora Benth.	1 (diarrhea)	0.89	2287.8	1664.7	-27.24	1534.5	-32.93	1423	-37.80
Pilosocereus pachycladus F. Ritter	1 (skin irritation)	0.80	6761.1	5356.8	-20.77	4798.8	-29.02	4631	-31.50
Piptadenia viridiflora (Kunth) Benth.	1 (anemia)	0.72	1915.8	1106.7	-42.23	1292.7	-32.52	1600	-16.50
Plathymenia reticulata Benth.	1 (cough)	0.91	3059.7	2278.5	-25.53	2083.2	-31.91	2083	-31.91
Poincianella pyramidalis (Tul.) LP Queiroz	1 (headache)	0.85	5291.7	3348	-36.73	2929.5	-44.64	2697	-49.03
Pseudobombax marginatum (A. St.- Hil., Juss. & Cambess.) A. Robyns	2 (cough, back pain)	0.82	1757.7	744	-57.67	520.8	-70.37	269.7	-84.66
Psidium guajava L.	3 (diarrhea, stomach pain, pain in the digestive organs)	0.79	2185.5	1915.8	-12.34	2408.7	10.21	3134	43.40
Psidium guineense Sw.	1 (diarrhea)	0.88	3338.7	3682.8	10.31	3757.2	12.53	3850	15.32
Psidium myrsinites DC.	2 (diarrhea, belly pain)	0.93	344.1	251.1	-27.03	223.2	-35.14	167.4	-51.35
Roupala Montana Aubl.	5 (liver disorders, stomach pain, back pain, leg pain, itching)	0.98	2455.2	1860	-24.24	1636.8	-33.33	1479	-39.77
Schinopsis brasiliensis Engl.	3 (diarrhea, cough, back pain)	0.90	16805	15038	-10.51	14415	-14.22	13708	-18.43

Senegal tenuifolia (L.) Britton & Rose	1 (cough)	0.81	3589.8	2362.2	-34.20	1785.6	-50.26	1302	-63.73
Senna spectabilis (DC.) HS Irwin & Barneby	3 (anemia, skin irritation, cough)	0.84	15587	14099	-9.55	13540.8	-13.13	13225	-15.16
Sideroxylon obtusifolium (Roem. & Schult.) TD Penn.	6 (diarrhea, liver disorders, renal colic, muscle pain, cough, back pain)	0.85	10174	7653.9	-24.77	6649.5	-34.64	5794	-43.05
Spondias mombin L.	3 (anemia, diarrhea, muscle pain)	0.74	269.7	241.8	-10.34	204.6	-24.14	176.7	-34.48
Spondias tuberosa Rue	4 (diarrhea, dehydration, body aches, stomach pain)	0.78	17996	17568	-2.38	18432.6	2.43	19130	6.30
Sterculia striata A. St.-Hil. & Naudin	1 (body pain)	0.89	855.6	660.3	-22.83	976.5	14.13	1190	39.13
Stryphnodendron rotundifolium Mart.	5 (anemia, skin irritation, liver disorders, stomach pain, bone pain)	0.91	1441.5	976.5	-32.26	799.8	-44.52	669.6	-53.55
Syagrus coronata (Mart.) Becc.	1 (cough)	0.92	2715.6	1562.4	-42.47	1181.1	-56.51	771.9	-71.58
Tabebuia aurea (Silva Manso) Benth. & Hook.f. ex S. Moore	1 (cough)	0.89	6119.4	4371	-28.57	3468.9	-43.31	2939	-51.98
Talisia esculenta (Cambess.) Radlk.	2 (diarrhea, dehydration)	0.84	2687.7	1906.5	-29.07	1897.2	-29.41	2000	-25.61
Terminalia glabrescens Mart.	1 (diarrhea)	0.93	1683.3	1292.7	-23.20	1088.1	-35.36	948.6	-43.65
Tocoyena formosa (Cham. & Schltdl.) K. Schum.	1 (headache)	0.86	11606	10100	-12.98	9504.6	-18.11	9672	-16.67
Triplaris gardneriana Wedd.	2 (cough, back pain)	0.80	6212.4	8193.3	31.89	14005.8	125.45	16275	161.98
Vitex gardneriana Schauer	1 (cough)	0.92	2250.6	1292.7	-42.56	1404.3	-37.60	1479	-34.30
Ximenia americana L.	10 (anemia, itching, diarrhea, headache, skin irritation, liver disorders, cough, stomach pain, back pain, fever)	0.72	4984.8	3961.8	-20.52	3487.5	-30.04	3153	-36.75
Zanthoxylum gardneri Engl.	2 (diarrhea, headache)	0.98	269.7	148.8	-44.83	93	-65.52	37.2	-86.21
Ziziphus cotinifolia Reissek	1 (liver disorders)	0.73	818.4	632.4	-22.73	771.9	-5.68	1190	45.45
Ziziphus joazeiro Mart.	7 (fever, anemia, itching, diarrhea, liver disorders, cough, stomach pain)	0.75	7477.2	6789	-9.20	7226.1	-3.36	8017	7.21

Discussion

Increasing climate severity will reduce the extent of favorable areas for the occurrence of most woody medicinal plant species in the semiarid region of Brazil, signaling future climates with lower availability of medicinal plants, as recorded in semiarid regions of other countries, such as Nepal, India, Kenya, Greece, Mexico, South Africa, Marocco, and the United States (Souther & McGraw 2014, Kachmar *et al.* 2021, Kumar & Rawat 2022, Tshabalala *et al.* 2022, Kunwar *et al.* 2023, Kougioumoutzis *et al.* 2024, El-Ghazouani *et al.* 2024, Radi *et al.* 2024, Márquez-Rangel *et al.* 2025). This finding is worrying, as climate change will also increase the incidence of several diseases (McMichael 2003, Moreira *et al.* 2020, Romanello *et al.* 2023), thereby increasing the demand for medicinal resources from forests.

According to Pant *et al.* (2021), 80% of the world's population uses medicinal plants to treat illnesses, indicating that the trend toward reduced availability of medicinal plants is a global problem. This fact, combined with the increased incidence of CSD, can increase risks to the health systems of different countries, especially those in semiarid regions of the planet, which are home to approximately 2.5 billion people, most of whom are economically vulnerable (Albuquerque *et al.* 2017, Scholes 2020, El-Ghazouani *et al.* 2024, Bouchaou *et al.* 2024). This is a challenging problem and requires an urgent, careful assessment of the consequences of reducing medicinal plant availability for the safety and well-being of populations, as environmental integrity is fundamental to human health (Mago *et al.* 2024, Milazzo *et al.* 2025).

In addition, the trend of reduction in medicinal plant availability from this and other studies (Kachmar *et al.* 2021, Cavalcante & Sampaio 2022, Kumar & Rawat 2022, Exposito-Alonso 2023, Kunwar *et al.* 2023, Silva *et al.* 2024, Kougioumoutzis *et al.* 2024, Radi *et al.* 2024, Sherestha *et al.* 2022; McCulloch-Jones *et al.* 2025), points to the negative impact of climate change on the structuring and resilience of LMS, which are pretty complex and adaptive (Kleinman 1978, Albuquerque *et al.* 2024). According to Ferreira Júnior *et al.* (2015), the utilitarian redundancy of LMS is a key component for their resilience, contributing to the adaptative value of local populations in the face of environmental risks, including the negative of climate change (Medeiros *et al.* 2020, Coe & Gaoue 2021).

Although the models indicate a reduction in areas favorable for the occurrence of many species, especially in scenarios 4.5 and 8.5, we did not detect the loss of any species in any of the scenarios, which is positive for maintaining functional redundancy and, consequently, the resilience of the LMS. However, the reduction in the availability of medicinal plants observed across different climate scenarios signals limitations in future therapeutic alternatives. This reduction, also reported in other semiarid regions of the world (Souther & McGraw 2014, Kachmar *et al.* 2021, Kumar & Rawat 2022, Kunwar *et al.* 2023, Kougioumoutzis *et al.* 2024, El-Ghazouani *et al.* 2024, Radi *et al.* 2024, Márquez-Rangel *et al.* 2025), may influence the role of the functional redundancy of LMS, and should be further investigated in future studies across different locations. Thus, although functional redundancy at the species level can be maintained, in more restrictive climate scenarios, the contraction of areas favorable for species occurrence may weaken or modify the practical flexibility and adaptative capacity of LMS by favoring the discontinuation of the use of scarce or less accessible resources and, consequently, weakening the system's flexibility. This demonstrates that increased climate severity may affect LMS, as hypothesized in this study. In other words, lower effective availability of medicinal resources can make access to them more difficult and influence species selection, as well as the collection and use of plants by local populations, with direct consequences for public health.

Furthermore, the risk of discontinuing the use of a medicinal resource previously attributed to predominantly cognitive factors, such as language (Albuquerque *et al.* 2024), is now understood as a concrete and relevant negative factor in understanding the dynamics of LMS. Increasing climate severity could trigger a cascade of effects in semiarid regions and alter the local relationships between people and species used to treat symptoms, potentially altering the structure of LMS. Over time, the limited availability of medicinal plants may result in changes in foraging strategies and resource management for treating illnesses, leading to the emergence of coevolutionary responses or increased use of biomedical remedies, which may influence the local transmission of medicinal knowledge (Applequist *et al.* 2020, Souza *et al.* 2022, Dantas *et al.* 2024) and need to be investigated in future studies.

For example, restrictions on the availability of medicinal plants can accelerate the process of sociocultural adaptation, whether through the incorporation of new knowledge, the redefinition of the use of historically less valued species, or even the search for alternatives outside the local traditional repertoire (Applequist *et al.* 2020). Such adaptation movements, while partially mitigating the reduction of therapeutic alternatives, can also trigger changes in traditional health care methods, affect the symbolic well-being of communities, weaken cooperative bonds between community members, and hinder the transmission of knowledge between generations, aspects that are fundamental to the sociocultural resilience of

LMS (Reyes-García *et al.* 2013, Ferreira Júnior *et al.* 2015, Albuquerque *et al.* 2024), and may ultimately increase the health vulnerability of some areas.

Another aspect to consider is that changes in climate characteristics can affect plant phenological cycles, such as leaf production, flowering, and fruiting periods (Kougioumoutzis *et al.* 2024, Aguiar *et al.* 2024, Jangpangi *et al.* 2025, Silva-Filha *et al.* 2025), potentially creating temporal mismatches between the availability of medicinal resources and the periods when communities traditionally carry out their collection (Lins Neto *et al.* 2021). In addition, climate change can induce changes in the adaptive physiological responses of plants to reduce the effects of thermal, water, and light stresses. This can modify the quality of the secondary compounds produced (Kougioumoutzis *et al.* 2024, Pant *et al.* 2021) and their efficiency in treating diseases. The change in secondary compounds when perceived and learned by local populations can negatively impact the LMS. Therefore, plant adaptive responses also influence LMS resilience, as even readily available resources may be discontinued over time if their efficiency is reduced or lost, signaling the possibility of changes in local cultures (Reyes-García *et al.* 2013).

It is worth noting that although climate scenarios were projected for the 83 species that constitute therapeutic alternatives for treating CSD symptoms, many of them are also used to treat other diseases in the Caatinga region (Campos & Albuquerque 2021), which intensifies people's search for medicinal plants in the LMS. Although some species' favorable ranges expand, this expansion does not necessarily offset the reduction in species numbers, because those that expand treat only a small number of symptoms. The treatment of more than half of CSD symptoms will be negatively impacted by climate change, especially in the most critical climate scenarios. In the context of LMS, recent discussions (Applequist *et al.* 2020, Campos & Albuquerque 2021) have shown that the dynamics between supply, demand, and functional arrangement of medicinal plants tend to intensify if they have multiple uses, including destructive ones, such as firewood, fencing, and construction (Nascimento *et al.* 2019). Overlapping uses intensify pressure on certain species, as demand for energy, construction, or food can directly compete with their medicinal uses, accelerating the decline of plant populations, even if the areas are favorable for the species. Therefore, species benefiting from climate change will not necessarily reduce the medical system's vulnerability if they treat only a few symptoms and have other frequent non-medical uses. Therefore, the effective reduction in the availability of therapeutic species may have consequences for biodiversity conservation, as well as for the resilience of LMS.

The cascade of consequences of climate change on the LMS increases its complexity, indicating the need for ongoing, interactive multilevel assessments (Berkes & Turner 2006) to better understand its dynamics of self-organization, learning, and adaptive value in the face of new realities. Current sociocultural adaptations in semiarid regions may not be sufficient to compensate for the scarcity of medicinal resources, exposing local populations to greater health risks. For example, muscle pain, a symptom of four of the CSD (zika, dengue, chikungunya, and yellow fever), will have severely reduced species availability, suggesting greater limitations for its treatment.

The future outlook highlighted in this study is one of increased health risks and an overload on public health systems in semiarid regions, indicating that effective coping strategies must go beyond simply maintaining species stocks, as suggested by Mykhailenko et al. (2025). In other words, they must incorporate measures to mitigate climate impacts, promote therapeutic knowledge of more resilient plant species, and sustainably use species with greater versatility. Identifying the risks and monitoring the signs of depletion of a given medicinal resource is a strategic task for health planning and biocultural conservation in the region.

Although this study projected negative changes in the availability of medicinal resources used to treat CSD, with consequences for LMS, it is necessary to recognize certain limitations that should be considered to improve our understanding of the impacts of climate change on LMS, which are inherently complex. Only woody species were considered in the analysis. However, the richness of herbaceous species in the Caatinga is high and, although most have temporally limited availability due to the rainy season (Araújo *et al.* 2007, Aguiar *et al.* 2024), many have medicinal value (Zank *et al.* 2015, Farias *et al.* 2019, Cunha *et al.* 2022) and can function as an important therapeutic alternative for the treating some symptoms of CSD in case of reduced local availability of a particular woody species. In addition, in many locations in the semiarid region, local populations adopt the practice of cultivating herbaceous medicinal resources (native and exotic) in their backyards (Zank *et al.* 2015) maintaining them with irrigation, which increases their potential use as a therapeutic alternative to woody resources that may become less available.

Another limitation is that the modeling performed only estimated the environmental suitability and potential distribution of species based on climatic variables, without incorporating variables related to physiological, demographic, and phenological processes of the species, as well as variables related to resource access and use or land-use change, which should be addressed to improve the accuracy of climate scenario projections for LMS.

The discussion regarding the adaptive value of LMS could be improved if future studies incorporate variables related to people's perceptions of the effects of climate change on the availability of resources for treating CSD symptoms, as well as the adaptive strategies adopted in the absence or reduction of particular therapeutic resources. Although overcoming the indicated limitations is not straightforward, future studies should identify the variables that best address these gaps, enabling a more comprehensive discussion of the challenges posed by change for CSD and public health.

Conclusion

The biodiversity service provided for public health will face risks with climate change. The reduced availability of medicinal plants is a global problem with serious consequences for the management of public health systems in semiarid regions. It may increase the social vulnerability of populations, especially low-income ones. This highlights the need for closer dialogue between public health and biodiversity conservation at the governmental and international levels. This is already being discussed in the One Health and Planetary Health approaches, which advocate for the integration of human, animal, and environmental health to maintain health and ensure sustainable and equitable management of Earth's resources (Mago *et al.* 2024, Milazzo *et al.* 2025, Redvers *et al.* 2025).

The ecological modeling approach used in this study showed that the climate crisis poses a concrete risk to the availability of several medicinal resources. The number of species that will experience reduced availability is high, and more than half of the symptoms of CSD will have limited treatment options with medicinal plants. The species that will experience increased availability treat a small number of CSD symptoms and do not outnumber the number that will experience a reduction. These findings demonstrate that increasing climate severity will exacerbate ecological problems, underscoring the importance of developing conservation strategies, especially for species that have experienced significant declines. Furthermore, climate change will increase the complexity of LMS and the health vulnerability of human populations in the different socio-ecological systems of semiarid regions, indicating the importance of valuing the transmission of local knowledge about medicinal plants to reduce health-related vulnerability; identifying the abandonment of traditional practices and the introduction of new therapeutic alternatives into LMS; and assessing how this abandonment and/or introduction would impact local culture, resilience, and the adaptive value of local medical systems.

Consequently, a government policy integrating biocultural conservation and public health must be encouraged in semiarid regions to address better the challenges posed by climate change. This policy can be a path to mitigating the risks of the climate crisis we face. Promoting the development of measures to monitor the availability of medicinal resources, encouraging community management practices and the cultivation of key species for diseases, especially those with high incidence, storing and preserving seeds, and continually evaluating the importance of these measures for the collection and use of resources by human populations are measures that need to be incorporated into this policy for the well-being of human populations and the conservation of the biological and cultural heritage of the regions.

Declarations

List of abbreviations: CSD - Climate-sensitive diseases; LMS - Local medical systems; SDM - Species distribution models; RCP - Representative Concentration Pathway; GBIF - Global Biodiversity Information Facility.

Ethics approval and consent to participate: This article does not contain any studies involving human participants or animals performed by any of the authors. Therefore, ethical approval and informed consent were not required.

Consent for publication: Not applicable.

Availability of data and materials: The datasets generated and/or analyzed during this study are available from the corresponding author upon reasonable request. Environmental and climatic data were obtained from the WorldClim database, and species occurrence records were obtained from the Global Biodiversity Information Facility (GBIF).

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Author contributions: EBS collected the data, conducted the analyses, and wrote the first version of the manuscript. UPA contributed to the study conception and methodology, participated in the analyses, and supervised the research. ELA contributed to the supervision and participated in the review of the manuscript. All authors contributed to the final version of the text.

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Supplementary Material: Standardized symptoms and their clinical variants / alternative terms, consolidated to harmonize the different terminologies found in the literature.

Standardized Symptom	Clinical Variants / Alternatives Terms
Anemia	anemia
Back pain	back pain; lumbago
Blood clotting disorders	blood clotting disorders; blood coagulation problems; coagulation disorders
Body aches	body ache; body aches
Cough	cough
Dehydration	dehydration
Diarrhea	diarrhea
Dizziness	dizziness; vertigo
Fever / High fever	fever; high fever
Headache	headache; cephalalgia
Itching	itching; pruritus
Joint pain	joint pain; arthralgia; joint find
Kidney involvement	kidney involvement; renal insufficiency; kidney colic; kidney stones; kidney pain
Liver disorders	liver disorders; liver problems; liver disease
Muscle pain	muscle pain; myalgia
Pain in digestive organs	pain in digestive organs; gastrointestinal pain
Pain in the abdomen	stomach pain; stomachache; abdominal pain; belly pain
Pain in the bones	cap pain; osseous pain
Pain in the legs	leg pain
Rash	skin irritation; skin rash; exanthema