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Natural distribution of yerba mate in Brazil in the current and future climatic scenarios

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ABSTRACT

Ilex paraguariensis St. Hill is a native species from Brazil, northeast of Argentina and Paraguay. It is mainly used in mate tea, a drink prepared by infusion of leaves. Nowadays, the species has sparked interest in its potential nutraceutical capacity and the presence of bioactive compounds for pharmacological and cosmetic use. The natural distribution area of the species is directly related to the climate. Thus, the predictability of occurrence, using appropriate niche models, is an important tool to assist in the adoption of species conservation strategies. Accordingly, aim of this work was to identify the natural distribution of the species, using ecological niche models, and project its distribution in future climatic scenarios, according to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. A tendency toward significant reduction in areas favorable to the distribution of yerba mate has been projected for future climatic scenarios, either "moderately pessimistic" (RCP4.5) or "more pessimistic" (RCP8.5), 71.7 and 78% in 2050 and 87 and 96.4% in 2070, respectively, showing a resultant trend toward concentration in the higher altitudes of the Atlantic Forest Biome. Thus, it is possible to predict the more favorable areas for conservation and breeding programs, ensuring the maintenance of its (da erva-mate) genetic diversity and resilience.

Introduction

Ilex paraguariensis St. Hill. (1822), popularly known as "erva-mate" in Brazil and "yerba mate" in Latin American countries, is a slow-growing and arboreal species. Its size can vary from a small to leafy tree with an estimated height between 3 to 8 meters for commercial cultivation. In forest communities, it reaches from 15 to 30 meters and 100 cm of diameter at breast height (dbh) with a cylindrical and slightly tortuous stem (Corrêa et al., 2000; Carvalho, 2003).

The canopy of yerba mate is generally low with a large volume of leaves showing a variety of sizes. The leaf morphology is simple: dark green on the upper face and lighter on the underside. The limbus is lanceolate or denticulate. Stipules are present next to the stem in most cases, usually exhibiting no hairiness; however, in some cases, this characteristic may appear. Their stipules appearance may vary from subcoriaceous to coriaceous, and their arrangement along the stem alternates (Carvalho, 2003).

In the forest environment, the leaves can grow up to 18 cm in length and 5 cm in width (Resende, 2001). The petiole is observed in white, purple or yellow colors (Corrêa et al., 2000). Leaves, limbus and petiole are harvested for processing and manufacturing of mate.

Mate is mainly used to produce beverages and is extracted through the infusion of dry leaves. Nowadays, the species has sparked interest for the potential use of its raw material, nutraceutical capacity and the presence of bioactive compounds for pharmacological and cosmetic use. It is also used as a fertilizer, for food production, and as a bactericide and antioxidant. Its use also extends to environmental processes, such as reforestation, ornamentation, as well as sewage treatment and recycling of urban waste (Tetto, 2008).

Mate, also known as "chimarrão" in Brazil, is a traditional South American infused drink. Furthermore, it is the national drink in Argentina, Paraguay and Uruguay, and drinking is a common social practice in southern Brazil, Chile, Eastern Bolivia, Lebanon and Syria. This species is widely found associated with *Araucaria angustifolia* (Bert.) O. Kuntze. in the lower and middle strata of the "Forest with Araucaria" (or "Ombrophilous Mixed Forest").

Yerba mate is economically important in southern Brazil, accounting for 63.4% of global production, making Brazil the world's largest producer (Resende, 2001). Although, yerba mate has consistent production and enjoys a large commercial market in Brazil, Argentina, and Paraguay, its productivity has been falling by the lack of quality seedlings and the lack of more rigorous breeding programs (Gorenstein et al., 2007). Yerba mate is the forest crop of greatest commercial value among species that do not target wood as a final product, it is the species with the highest value of the production of non-timber forest species in the state of Paraná in 2018, with more than 50% of the R$ 689 million, of the forest production value of R $ 89.8 billion. Yerba mate was cultivated on more than 110,000 hectares, with the participation about 180,000 properties, generating more than 700,000 direct and indirect jobs and around 400 companies in Brazil. In 2019, in the state of Paraná, it represented more than R $ 656 million, in a planted area of 52,149 hectares and production of 547,888 tons (SEAB, 2020).

The area of natural occurrence is approximately 540,000 km^2, located in South America between latitudes 22º S and 30º S, longitudes 48º 30' W and 56º 10' W and altitudes between 500 and 1,500 meters (Rotta & Oliveira, 2010; Resende et al., 2000; Corrêa et al., 2000; Groppo, 2010). The natural distribution area of the species is directly related to the climate. Thus, the predictability of occurrence, using appropriate niche models (Muñoz et al., 2011), is an important tool to assist in the adoption of species conservation strategies. As such, the aim of this work was to identify the natural distribution of yerba mate in Brazil, using climatic variables and ecological niche models, projecting its distribution in future climatic scenarios, according to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5 / IPCC) (IPCC, 2014). The outcome of this study should make it possible to identify strategic areas for conservation, to develop future breeding programs, and find suitable places for new planting. More specifically, we calculate the reduction of favorable areas for yerba mate as a result of global climate change, considering two distinct climatic scenarios, one less pessimistic (RCP4.5) and other more pessimistic (RCP8.5).

Material and Methods

The study area comprises the South, Southeast and Midwest regions of Brazil. We studied the effect of climate change in these areas using selected models compiled and grouped by Worldclim (Fick & Hijmans, 2017), according to the Fifth Assessment Report of the IPCC (AR5 / IPCC) (IPCC, 2014) for the present period (1961-1990) and for the future scenarios of 2050 and 2070.

We analyzed the completeness and consistency of the data series, checking the presence points of yerba mate. Because of previous analyses, the outliers were eliminated since they do not represent areas of natural occurrence. However, they have been registered in the database for future review.

We grouped 518 presence points of yerba mate in Brazil obtained from different sources, including data collected by the National Forest Research Center (CNPF) of the Brazilian Agricultural Research Corporation (Embrapa). Literature data were obtained from several institutions: Escola Superior de Agricultura "Luiz de Queiroz" (ESALQ - USP), Universidade Estadual Paulista (UNESP), Universidade Federal do Paraná (UFPR) and SpeciesLink, the databases of biological collections of the Reference Center on Environmental Information (CRIA) (CRIA, 1999). SpeciesLink is a species information system that identifies fauna, flora and microbiota and gathers historical information from several sources (Brazilian herbaria) (INCT, 2020). The georreferenced points of occurrence from various bases were gathered in an electronic spreadsheet to process the species distribution model.

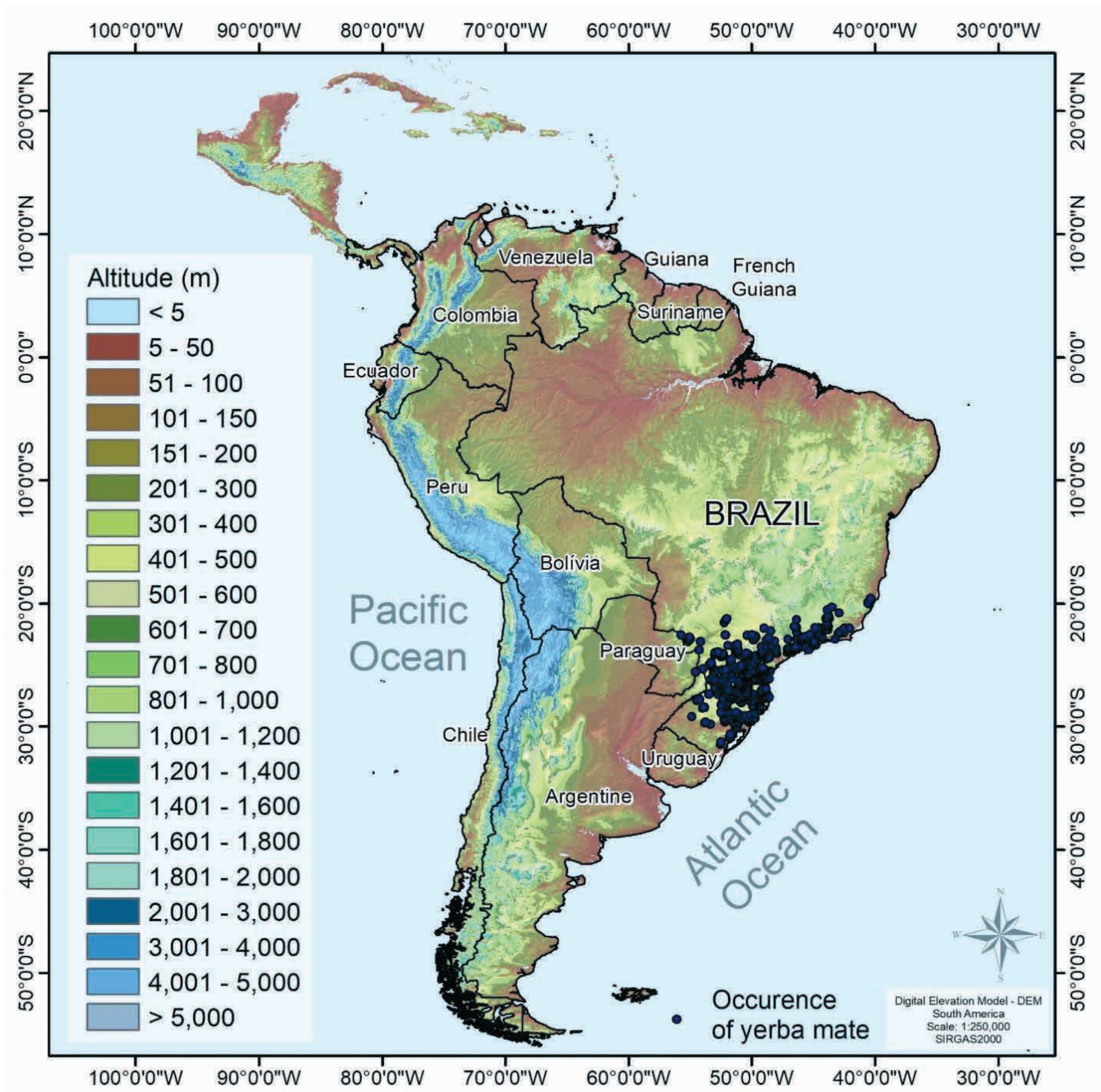
The climatic layers were elaborated in geographic information systems (GIS) using multiple linear regression so that the climatic data were correlated with the Digital Elevation Model (DEM), as well as latitude and longitude

(Weber & Hasenack, 2004; USGS, 1999) (Figure 1).

We used two different scenarios: RCP4.5 and RCP8.5. According to the Fifth Assessment Report of the International Panel on Climate Change (AR5 / IPCC) (IPCC, 2014), emissions of anthropogenic Greenhouse Gases (GHG) are mainly driven by population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy. The Representative Concentration Pathways (RCPs), which are used for making projections based on these factors, describe four different 21st century pathways of GHG emissions, including atmospheric concentrations, air pollutant emissions and land use. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5). RCP4.5 is an intermediate stabilization pathway in which radiative forcing is stabilized at approximately 4.5 W/m^2 after 2100. RCP8.5 is one high pathway for which radiative forcing reaches 8.5 W/m^2 by 2100 and continues to rise for some amount of time.

We used the Environmental Distance Algorithm (Muñoz et al., 2011) to predict the occurrence of yerba mate in Brazil. The model identifies the species based on local climate conditions. The algorithm normalizes the values of environmental variables, calculates the distance between environmental conditions for each point of occurrence, and selects the shortest distance. If the calculated distance value is between "0" and the "supplied parameter" value, then the probability of occurrence will range between "0" and "1". If the value is higher than the parameter

Figure 1. Occurrence of yerba mate in Brazil and hypsometric layer (Digital Elevation Model – DEM) (Weber and Hasenack, 2004) adapted from USGS (1999).



value, then the probability is "0". We chose this algorithm because it best represents the natural conditions for the occurrence of yerba mate (better Area Under Curve - AUC).

The following climatic variables were used from Worldclim (Fick & Hijmans, 2017): maximum and minimum air temperature, annual rainfall and relative air humidity in the summer (in Southern Hemisphere - December, January, February), autumn (March, April, May), winter (June, July, August) and spring (September, October, November).

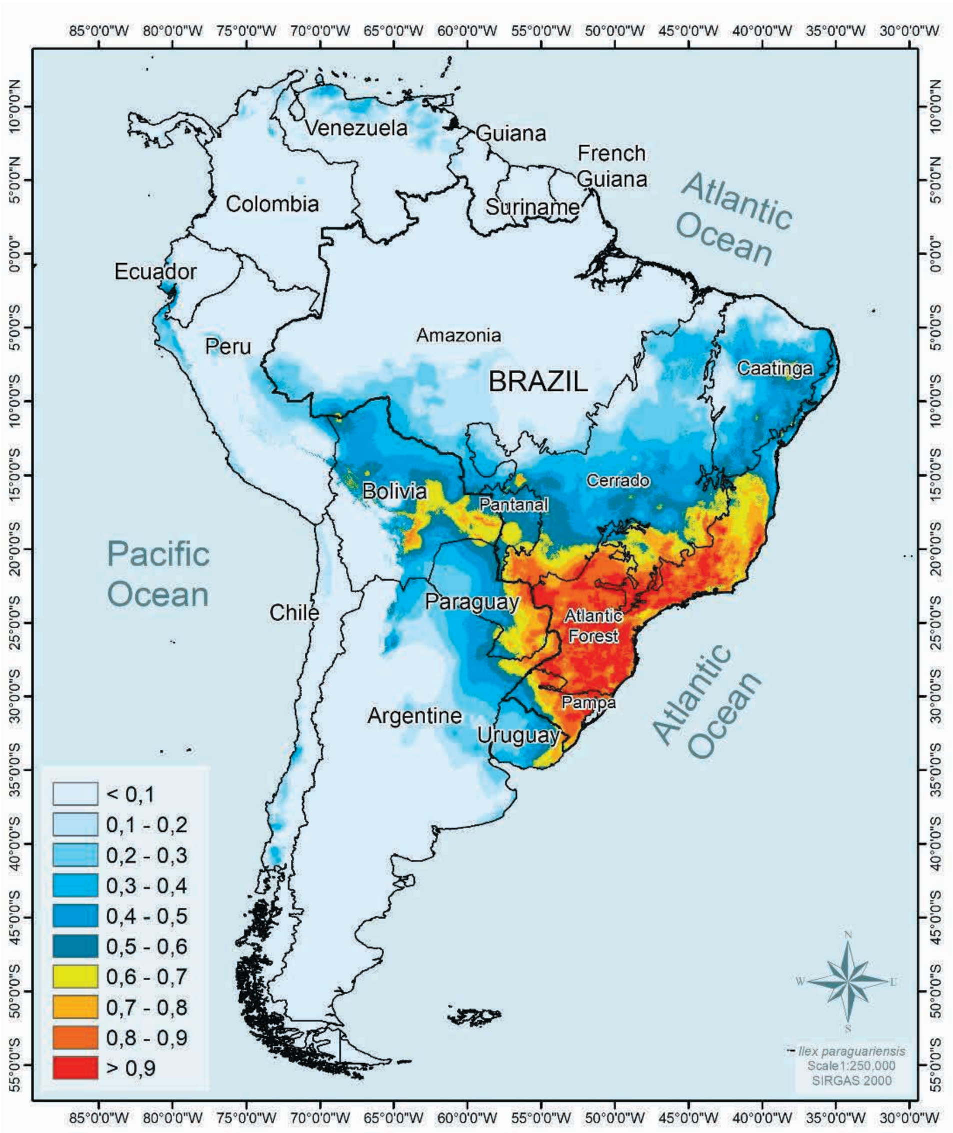
The computational forecasting Open Modeller software was used to estimate the geographical distribution of species based on the geographical coordinates (latitude and longitude) and environmental layers (climate, soil, altitude and landscape) (Muñoz et al. 2011).

The software generates a text file (ArcInfo AscGRID), which we integrated into the ArcMap software (ESRI, 2011) in raster format, using geographic coordinate systems and the SIRGAS2000 Datum. The layers of current and future scenarios were divided into two classes by making a cutoff point at 0.5 (between 0 and 1) such that class 1 (≤0.5) is unfavorable, while class 2 (> 0.5) is favorable for the development of the yerba mate. The layers were transformed into a vector that intersected with the biome layer. The coordinate systems were redefined for UTM, SIRGAS2000 Datum (Zone 21 S), and the favorable areas per biome were calculated in the current and future scenarios.

Results and Discussion

The blue areas of the layer (Figure 2) represent the current areas of yerba mate occurrence, as defined by the Environmental Distance Algorithm. The red areas are satisfactory, and the blue areas are not satisfactory

Figure 2. Ecological niche of yerba mate based on Environmental Distance Algorithm on Brazilian Biomes. Red represents the highest probability of occurrence (>0.5) (highly favorable) and blue, low probability (≤0.5) (less favorable).



for species development. The same is true for the future scenarios (Figures 2 to 6). In the future, potential areas for the development of yerba mate in 2050 and 2070 are represented in two different scenarios: RCP4.5, less pessimistic, and RCP8.5, more pessimistic. We identified areas that should be prioritized for conservation programs of natural yerba mate populations and favorable areas for planting.

Some layers of climatic variables were used to model the distribution occurrence of yerba mate and define the boundaries. A limited number of bioclimatic variables can be used to model the yerba mate niche. Huntley et al. (2004) state that "the distribution of species from different taxonomic groups, representing different life forms and trophic levels, can be modeled successfully using a limited number of bioclimatic variables".

The simulation was significant (P <0.001), with high values of AUC (1), Internal Test (0.9998), External Test (0.9897) and 0% of omission error. In the resulting layer, a potential area for the planting of yerba mate was identified. It corresponds to more than 150 million hectares in the mountainous areas of Southern, Southeastern and Midwest Brazil. However, in 2050, this same area is predicted to be less than 43 million hectares, a 72.3% decrease, according to the less pessimistic scenario (RCP4.5), or less than 34 million hectares, a 78.5 % decrease, according to the most pessimistic scenario (RCP8.5). In Brazil, no suitable area will exist for the development of the species after 2070, except in São Joaquim, a municipality with the highest altitude in the State of Santa Catarina and an ideal place for species conservation and the development of a genetic breeding program. In other regions, climatic conditions will become unfavorable and the risk of yerba mate not developing properly or not completing its natural life cycle

Figure 3. RCP4.5 - 2050 - Change of yerba mate occurrence niche based on the Environmental Distance Algorithm, according to the global climate change scenario, on Brazilian Biomes. Red represents the highest probability of occurrence (>0.5) (highly favorable) and blue, low probability (≤0.5) (less favorable).

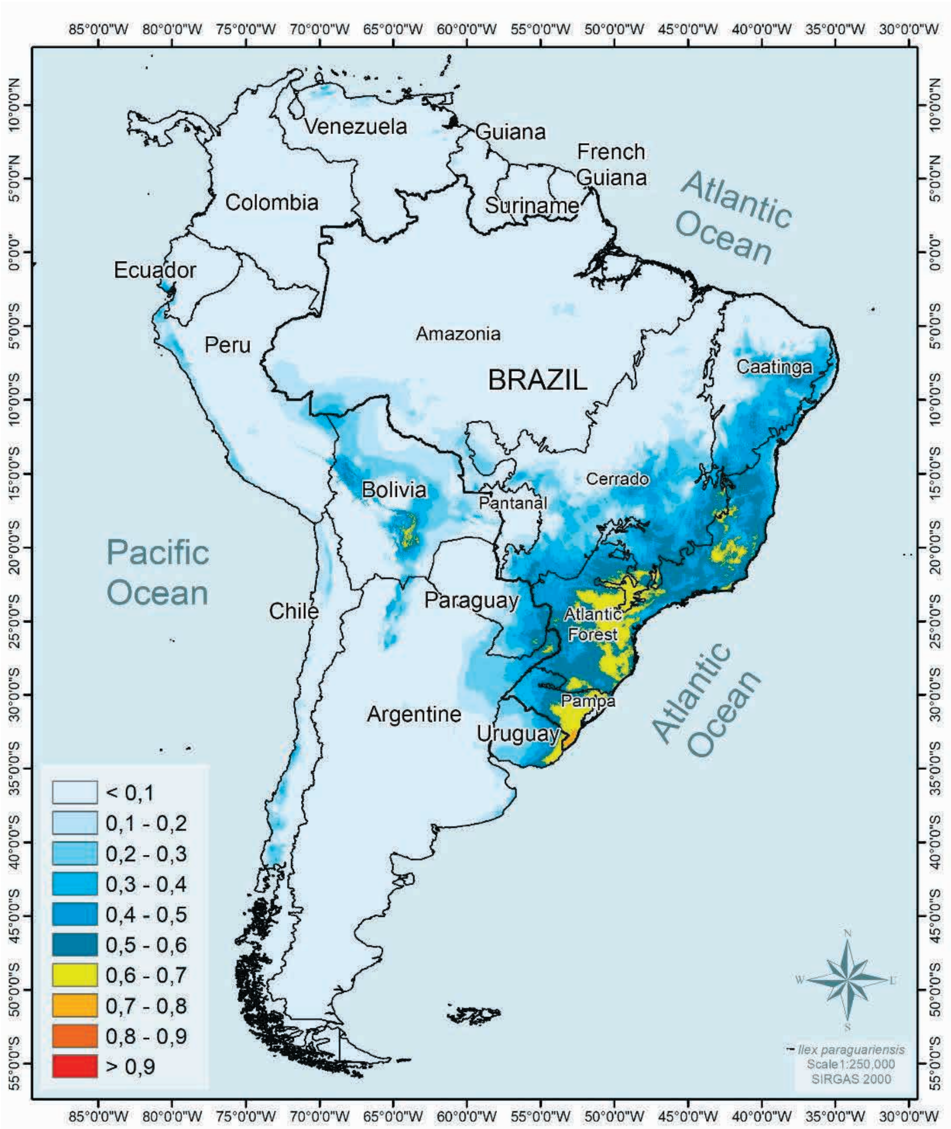
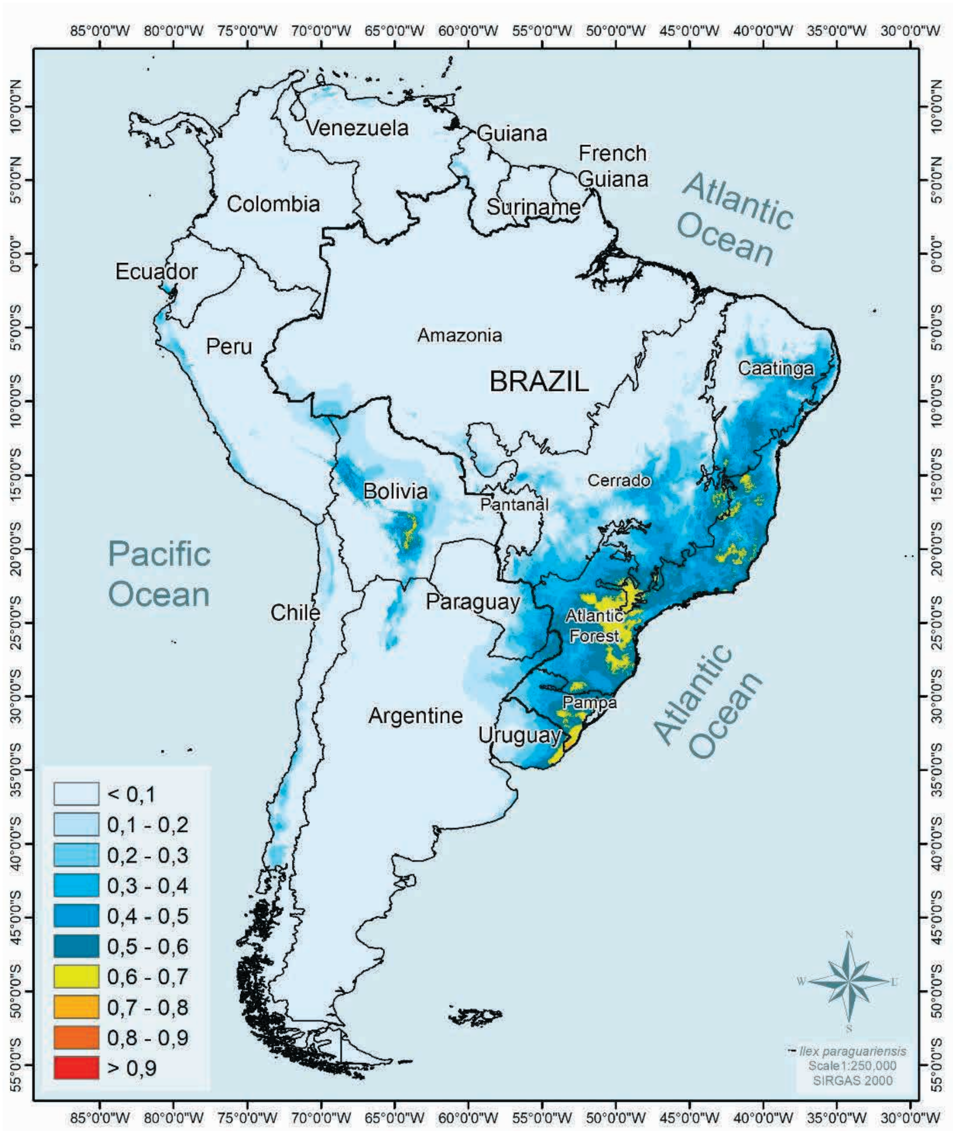


Figure 4. RCP4.5 - 2070 - Change of yerba mate occurrence niche based on the Environmental Distance Algorithm, according to the global climate change scenario, on Brazilian Biomes. Red represents the highest probability of occurrence (>0.5) (highly favorable) and blue, low probability (≤0.5) (less favorable).



will be high. The reduction in favorable area will occur in all biomes (Table 1).

In view of these new scenarios, natural populations subject to a more intense climatic regime should be prioritized for *ex situ* conservation. The conservation of those populations will be strategic for the future of the species since these stands will act as a genetic reservoir that may have already adapted to the increase in temperature and other climatic variables (Pye & Gadek, 2004). In general, attempts to conserve the species must consider both the divergence between populations and the diversity within populations, especially for *ex situ* conservation (Petit et al., 1998).

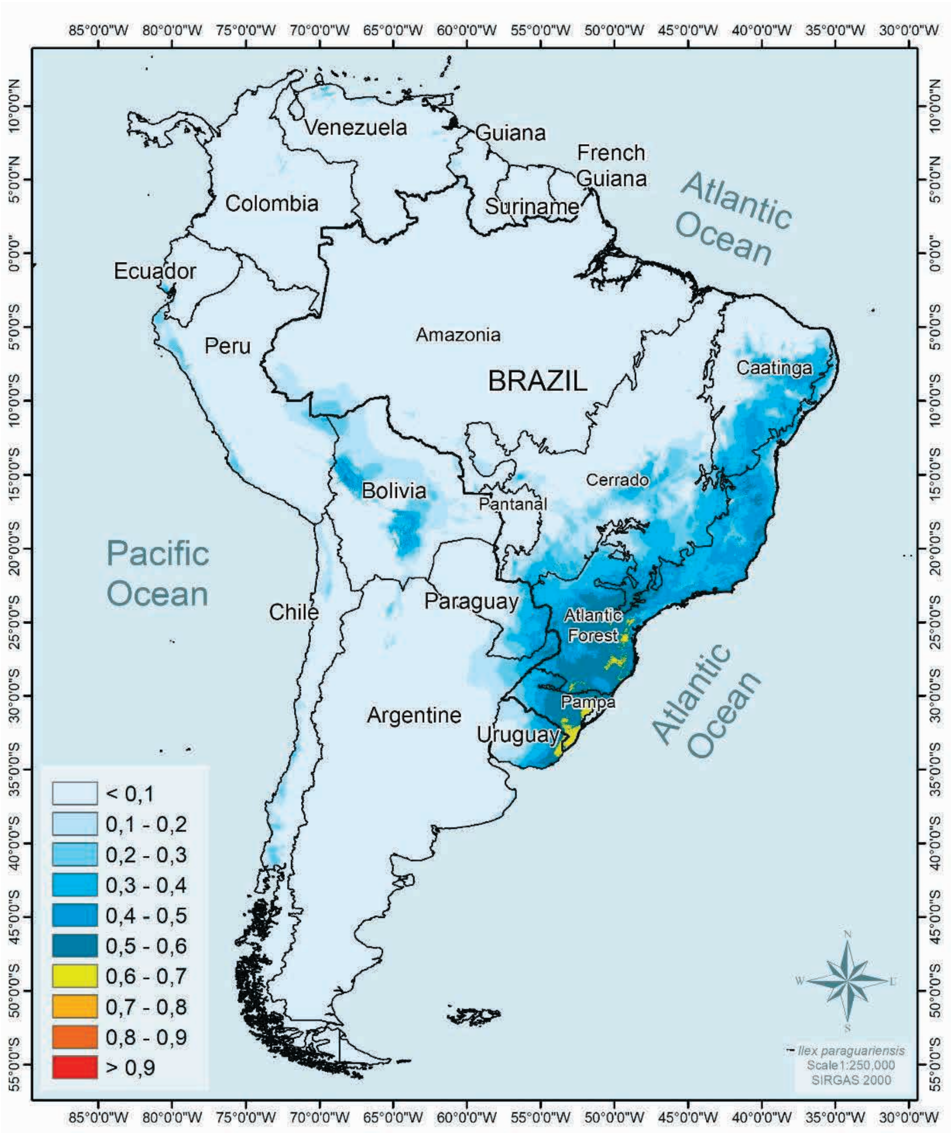
The collection of genetic material from yerba mate in protected areas must be a priority to build an active germplasm bank to preserve the genetic diversity of the species (Table 1), as well as in areas with extreme climatic conditions. Such areas include the extreme southwestern part of the State of Paraná (Foz do Iguaçu) where temperatures are higher, the southern area of Rio Grande do Sul State where water availability is lower, especially in the summer when compared to other Brazilian areas (Wrege et al., 2011), or in the Brazilian Midwest. This mate material may be used in future breeding programs, for commercial use, or even for replacement, i.e., ecosystems restoration, in nature where it will be more difficult to find.

According to Chou et al. (2014), in the climate change scenarios, species will be found more frequently in areas of higher altitude and latitude where climate is colder and wetter. It is very likely that other forests surrounding the Ombrophilous Mixed Forest will expand owing to

Table 1. Changes in favorable areas (hectares) for yerba mate in Brazil based on global climate change.

Biome	Current	RCP4.5 2050	RCP4.5 2070	RCP8.5 2050	RCP8.5 2070
Atlantic Forest	98,010,776.6	30,342,643.3	13,922,594.0	22,138,957.4	3,591,410.4
Pampa	13,422,953.1	10,274,909.3	2,797,917.8	6,602,572.4	1,305,133.3
Cerrado	40,053,629.8	2,121,035.2	2,985,335.9	4,452,469.3	449,361.4
Pantanal	3,186,383.2	0	0	0	0

Figure 5. RCP8.5 - 2050 - Change of yerba mate occurrence niche based on the Environmental Distance Algorithm, according to the global climate change scenario, on Brazilian Biomes. Red represents the highest probability of occurrence (>0.5) (highly favorable) and blue, low probability (≤0.5) (less favorable).



their faster development concurrent with increasing temperatures and decreasing areas favorable to the occurrence of yerba mate. These areas would include the Semidecidual Seasonal Forest that occurs in the north, northwest, southwest and western part of the State of Paraná, or the Ombrophilous Dense Forest, and vegetation that occurs in the coastal and some areas of the Ribeira Valley.

Yerba mate is found between 1 and 1,390 meters in altitude (Table 2). The minimum temperature in winter is between 5.4 and 13.0°C, reaching - 8.5°C (absolute minimum temperatures), and the maximum temperature in summer is between 23.3 °C and 31 °C, reaching to more than 39 °C (absolute maximum temperatures) (Table 3). This species is found more frequently in areas with temperatures ranging from -2 °C to 35 °C with rainfall between 1,500 mm to 1,800 mm, varying between 1,400 mm to 2,200 mm. However, some yerba mate populations are located in areas

Table 2. Rainfall (P) (mm), water balance (P-ETP) (mm), and altitude (meters) in favorable areas in southern Brazil for yerba mate.

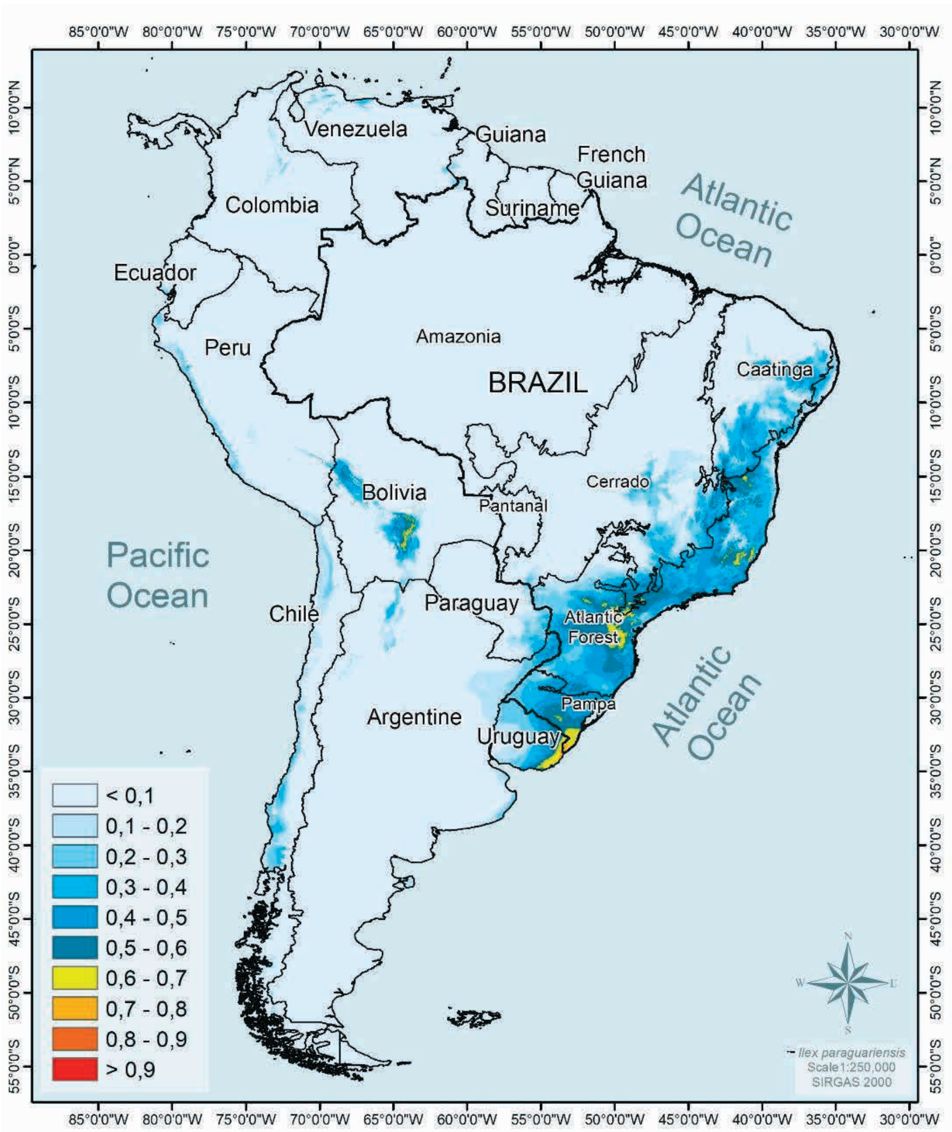
	Rainfall	County	P-ETP	County	Altitude	County
Lower value	1450.97	Guaíba (RS)	561.38	Guaíba (RS)	1	Torres (RS)
Highest value	2323.87	Paranaguá (PR)	1397.52	Paranaguá (PR)	1390	São Joaquim (SC)

Table 3. Air temperature (oC) in favorable areas of southern Brazil for yerba mate.

	tmn abs	County	tmn	County	tmx abs	County	tmx	County
Lower value	-8.57	São Joaquim (SC)	5.46	São Joaquim (SC)	30.24	São Joaquim (SC)	23.35	São Joaquim (SC)
Highest value	5.07	Foz do Iguaçu (PR)	13.05	Paranaguá (PR)	39.07	Paranaguá (PR)	31.60	Foz do Iguaçu (PR)

Note: tmn abs is the average absolute minimum temperature; tmn is the average of the minimum temperatures; tmx abs is the average of the absolute maximum temperatures; tmx is the average of the maximum temperatures; P is rainfall; P-ETP is rainfall less potential evapotranspiration

Figure 6. RCP8.5 - 2070 - Change of yerba mate occurrence niche based on the Environmental Distance Algorithm, according to the global climate change scenario, on Brazilian Biomes. Red represents the highest probability of occurrence (>0.5) (highly favorable) and blue, low probability (≤0.5) (less favorable).



where extremes of rainfall and temperature are recorded (Partala, 2011).

In a few decades, major changes are expected to increase our planet's average temperature by 1.8 °C to 6.3 °C (IPCC, 2014), and this will be unprecedented in our planet's history. In the past geological ages, climate change has occurred, but the changes were slow, taking hundreds of generations, with enough time for plants to develop the evolutionary mechanisms necessary to reduce the difficulties of adaptation, including migration, selection, drift and mutation; and, thus, reduce the risks of species extinction.

The displacement of the species according to elevation in altitude at the same latitude should be 227m to 797m in order to compensate for temperature rise, considering an adiabatic gradient with reduction of the average air temperature of 0.79 °C every 100 m of altitude in the southern area of Brazil (Fritzsons et al., 2016, 2015).

Considering that the full effects of climate change will start to be felt within 100 years, yerba mate will not have sufficient time to adapt to the new conditions spontaneously in nature. This shortfall in adaptive capability could be directly proportional to the evolving greenhouse gases emitted in the atmosphere (Wrege et al., 2009). The negative effects caused by the decline and fragmentation of yerba mate populations will only be evident after many generations, as will araucaria (Sousa, 2001).

Yerba mate is a species of great plasticity, but it is vulnerable to climate change, as the data in this work indicate. Changes in flowering and seed germination will reduce the capacity for regeneration and growth. The vulnerability may worsen with increasing herbivory and diseases, as well as increasing wildfires and competition with invasive species.

Therefore, genetic diversity must be conserved in order to allow the species time to adapt to evolving environmental conditions. The survival of yerba mate, as well as other native species, is related to the dispersion capacity of its seeds and the ability to reproduce, which will be modified with global climate change (Bittencourt & Sebbenn, 2007), except in areas of higher altitude and latitude.

The regeneration capacity of yerba mate is considered enough to guarantee its survival, but if climate change continues as the same way, the risk of losing many proceedence will be high. Therefore, preference should be given to the collection of genetic material of the species to compose an active germplasm bank in regions of extreme climatic events, at the edge of distribution and climate transition zones, which may occur, for example, in the Midwest and the Southeast Brazil.

It is important to conserve areas at the highest altitude and latitude to ensure survival of the species, especially in the States of Santa Catarina and Rio Grande do Sul.

This article portends a reduction of area with potential for the development of the species. However, the projections presented in this work should be evaluated in consideration of other factors influencing the development of the species. The current scenario will not be the same with rising temperatures. We recommend intensive efforts to monitor yerba mate populations in the coming decades. Furthermore, a better understanding of the direct and indirect effects of global climate change on yerba mate and on the occurrence of its natural competitors is needed.

It should be a priority to collect native yerba mate material in the preserved regions where climatic extremes are recorded, especially high temperatures and in areas with higher frequency of droughts, to build active germplasm banks and preserve the genetic diversity of the species.

Conclusions

Priority sites for the conservation programs of natural populations of yerba mate *in situ* can be defined by means of ecological niche modeling, choosing the climatic variables of higher relevance for this purpose.

The distribution prediction presented in this paper may be useful for the selection of new areas for planting yerba mate in Brazil.

Global climate change could bring threats to yerba mate because it is a species adapted to cold weather and depends on low temperatures to complete its life cycle.

The preservation of populations in the northern and southern limits of the regions of natural occurrence of the species can guarantee a greater genetic diversity. It will allow a better response by the species to global climate change, especially in Mato Grosso do Sul, in the region of Caarapó, and in the extreme southern part of Rio Grande do Sul, in the region of Santana da Boa Vista, Canguçu and Pelotas, because each one represents a unique environment.

The best regions to conserve yerba mate populations are the highest altitude areas in southern Brazil, mainly near the municipality of São Joaquim where the lowest temperatures in Brazil are recorded and where, even in the climate scenarios projected for the year 2070, climatic conditions will still be favorable for its development.

Yerba mate will suffer a large reduction in area with climate change, from 71.7 and 78.1% in RCP4.5 in 2050 and 2070 and from 86.9 and 96.4% in RCP8.5 in 2050 and 2070, respectively.

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Author contribution

M. S. WREGE responsible for the Araucamate project, participated in field expeditions to obtain the geographic coordinates of yerba mate and wrote the main text of the article and elaborated the figures.

M. T. S. SOARES, E. FRITZSONS, V. A. SOUSA, A. V. AGUIAR, I. A. BOGNOLA and L. P. SOUSA participated in field expeditions to obtain the geographic coordinates of yerba mate and helped write the text of the article. They collected samples of leaves in the field and soil to compose a DNA bank and a database of soils, climate and bioactive elements and compounds present in yerba mate leaves

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Distribuição natural da erva-mate no Brasil no presente e nos cenários climáticos futuros

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RESUMO

Ilex paraguariensis St. Hill é uma espécie nativa do Brasil, Nordeste da Argentina e Paraguai. É utilizada principalmente no mate, bebida preparada pela infusão das folhas. Atualmente, a espécie tem despertado interesse pelo potencial de ampliação de uso, capacidade nutracêutica e presença de compostos bioativos de uso farmacológico e cosmético. Sua área de distribuição natural é diretamente relacionada aos aspectos climáticos. Portanto, é possível modelar sua distribuição usando modelo de nicho, que se constitui como ferramenta importante para auxiliar na adoção de estratégias de sua conservação e uso. O objetivo do trabalho foi identificar a distribuição natural da espécie, a partir de modelos de nicho ecológico, e projetar sua distribuição em cenários climáticos futuros, de acordo com o Quinto Relatório de Avaliação do Painel Intergovernamental de Mudanças Climáticas. A tendência é de ocorrer uma expressiva redução de área favorável à erva-mate nos cenários climáticos futuros "medianamente pessimista" (RCP4.5) e "mais pessimista" (RCP8.5), de 71,7 e 78% em 2050 e de 87 e 96,4% em 2070, respectivamente, com a espécie concentrando-se em áreas de maior altitude do Bioma Mata Atlântica. Assim, é possível indicar regiões mais favoráveis para sua conservação e futuro uso em programas de melhoramento genético e conservação, garantindo a manutenção de sua diversidade genética e capacidade de resiliência.

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