Climatic Zoning of Yerba Mate and Climate Change Projections: A CMIP6 Approach

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Abstract

Yerba mate (*Ilex paraguariensis*) has several nutritional and pharmaceutical properties and is traditionally used in South America in the preparation of various types of beverages. The pharmaceutical industry has a large number of patents for products related to the properties of this plant. This study aims to analyze the climatic zoning of the yerba mate relative to climate change using CMIP6 model projections. Understanding the potential effects of climate change on yerba mate production and distribution is essential due to its economic and cultural importance. The CMIP6 model allows the analysis of future scenarios by identifying favorable and unfavorable areas for cultivation. The results provide subsidies for adaptation and mitigation measures, helping in strategic planning and decision-making related to sustainable yerba mate production. This study aimed to identify favorable areas for *Ilex paraguariensis* cultivation for the main producing countries, that is, Brazil, Argentina, Paraguay, and Uruguay, under the CMIP 6 climate change scenarios. The study was conducted in producing regions of the North, Northeast, Midwest, Southeast, and South of Brazil and the countries Paraguay, Argentina, and Uruguay. The ideal air temperature for crop development ranges from 21 to 25°C and the ideal precipitation is > 1200 mm per cycle. Daily air temperature and precipitation data for the current scenario were collected using the WorldClim version 2 platform. Projections of future climate variables were obtained from the WorldClim 2.1 platform using the IPSL-CM6A-LR model, with a 30-second spatial resolution. Four shared socio-economic pathway scenarios were considered for four different periods: 2021–2040, 2041–2060, 2061–2081, and 2081–2100. Data from a geographic information system were used to carry out spatial interpolation throughout the Brazilian territory, using the Kriging method. The results showed that most of the studied territory is classified as unfavorable for yerba mate cultivation, with only 12.25% (1.5 million km^2) considered favorable. The highest concentration of favorable areas is found in the South of Brazil and Uruguay, which are currently the main producers of yerba mate. Most future scenarios of climate change showed a high impact on the climate due to an increase in the mean air temperature and a reduction in precipitation, leading to possible negative impacts on yerba mate cultivation, with a total reduction of favorable areas in producing regions.

Introduction

Yerba mate, or *Ilex paraguariensis*, is a plant native to the subtropical region of South America, found mainly in Brazil, Argentina, Paraguay, and Uruguay (ACEVEDO et al., 2019; GIBERTI, 1995). This plant has great cultural and economic importance in the region (CABRAL et al., 2020), having been used for centuries by indigenous communities as a source of food, medicine, and stimulant (HECK; DE MEJIA, 2007). Yerba mate has gained international prominence in recent years due to its nutritional and medicinal properties and its potential as an ingredient in beverages and foods (GERBER et al., 2023).

Yerba mate production is an important source of income for many rural communities in South America and the beverage and food industry, which use it as an ingredient (SAMOGGIA; LANDUZZI; VICIÉN, 2021). Brazil is the largest producer, with around 50% of global production, followed by Argentina (42%) and

Paraguay (9%). In 2019, Brazil produced approximately 880 thousand tons of yerba mate, Argentina produced 837 thousand tons, and Paraguay 171 thousand tons (FAO, 2020).

Ilex paraguariensis is a dioecious evergreen tree that can grow to a height of 8–15 m (BRACESCO et al., 2011). The flowering stage occurs during spring, producing small unisexual flowers that have four white petals (MAJID; FARAJ, 2022). The flowers may gather in clusters of 1 to 15 and appear in the leaf axils. The fruits consist of red berries containing 4 to 5 seeds (FERNANDES et al., 2017).

Yerba mate productivity and quality are closely related to climate conditions (BEHLING; PILLAR, 2007). The species develops better in regions with a mean annual temperature between 15 and 22°C and annual rainfall higher than 1200 mm (RICARDO et al., 2011). Yerba mate adaptation to these conditions means that its cultivation is restricted to areas with specific climate characteristics, limiting the geographic expansion of production (GONZÁLEZ et al., 2011).

Global climate change, resulting from human activities and the increase in the concentration of greenhouse gases, has impacted climate patterns in various regions worldwide (IPCC, 2021). These changes can directly affect the geographic distribution and productivity of crops, including yerba mate, in addition to increasing the vulnerability of the agricultural sector to climate variations (LOBELL; SCHLENKER; COSTA-ROBERTS, 2011).

Agroclimatic zoning is a useful tool for identifying favorable areas for the cultivation of species, considering climate conditions and the specific requirements of plants (RAMALHO et al., 2018). This approach allows for optimizing the use of natural resources, minimizing environmental impacts, and maximizing agricultural productivity (GRASSINI; ESKRIDGE; CASSMAN, 2013). It allows farmers to choose the most appropriate crops for each region, increasing productivity and reducing the risks associated with climate variations (TEIXEIRA et al., 2013).

In this context, understanding how climate change can affect yerba mate cultivation and identifying adaptation and mitigation strategies are essential. The analysis of agroclimatic zoning, considering future climate projections, is essential for the development of policies and actions to adapt to the new climate reality (HANNAH et al., 2013).

Thus, this study aimed to identify favorable areas for the cultivation of *Ilex paraguariensis* in the main producing countries, that is, Brazil, Argentina, Paraguay, and Uruguay, under CMIP 6 climate change scenarios.

Material and methods

The study was conducted in the main yerba mate-producing regions: North (1), Northeast (2), Midwest (3), Southeast (4), and South (5) of Brazil, in addition to the countries Paraguay (6), Argentina (7), and Uruguay (8). The predominant climate in the study regions comprises the tropical and subtropical climate classes according to the Köppen (1936) climate classification: Aw, Cfa, Cwa, and Cwb (ALVARES et al., 2013).

Daily air temperature and precipitation data for the current scenario were collected using the WorldClim version 2.1 platform (FICK; HIJMANS, 2017). These data cover the period of the last climatological normal (1991–2020) and are available in GeoTIFF format (.tif), with a 30-second spatial resolution (equivalent to 1 km^2). The yerba mate production data were collected from the Brazilian Institute of Geography and Statistics (IBGE, 2021).

Projections of future climate variables were obtained from the WorldClim 2.1 platform, by the IPSL-CM6A-LR model (BOUCHER et al., 2020) also with the 30-second spatial resolution. All shared socio-economic pathway (SSP) scenarios available for four different periods were considered: 2021–2040, 2041–2060, 2061–2081, and 2081–2100 (RIAHI et al., 2017). SSP scenarios are calculated based on the radiation reflection number and vary relative to the measures that society can adopt to reduce greenhouse gas emissions (DELLINK et al., 2017). These scenarios are classified as SSP-1 2.6 (optimistic), SSP-2 4.5 and SSP-3 6.0 (intermediate), and SSP-5 8.5 (pessimistic) (KRIEGLER et al., 2017; VAN VUUREN et al., 2017).

The climate conditions that influence *Ilex paraguariensis* development were defined based on the climate variables mean air temperature and precipitation. The ideal air temperature is 15 to 22°C and the ideal precipitation is > 1200 mm per cycle (KEMPER; SCHMIDT; KELLER, 2022; MILANI et al., 2020). Thus, these conditions were combined, generating the climate favorability key for yerba mate (Fig. 2).

Data from a geographic information system (GIS) were used to conduct spatial interpolation throughout the Brazilian territory, using the Kriging method (KRIGE, 1951) with a spherical model and a 0.25° resolution. Kriging is a geostatistical method widely recognized for its efficiency in data interpolation (CARVALHO; ASSAD; PINTO, 2012). It allowed obtaining the climatic zoning for yerba mate in Brazil. The software Quantum GIS (QGIS) 3.16.4 was used to prepare the mapping.

Results and discussion

Yerba mate (*Ilex paraguariensis*) zoning indicated that most of the study area was classified as unfavorable for cultivation (Fig. 3). The studied area presented 12.2% (1.5 million km^2) of its territory as favorable for yerba mate cultivation, standing out the South region of Brazil (5) (96.7% or 543 thousand km^2) and Uruguay (81.2% or 144 thousand km^2), which concentrate the largest favorable areas (Table 1). The South region stood out, as it is one of the largest yerba mate producers in Brazil, with an annual production of 557 thousand tons (IBGE, 2021). Argentina (7) presented the largest areas classified as relatively favorable (44.6% or 1.2 million km^2). The North region of Brazil (1) had the largest areas unfavorable for yerba mate cultivation (99.8% or 3.9 million km^2), mainly due to the high temperatures in the region, making it impossible for the plant to bear fruits (BRITO FILHO; SANTOS, 2014).

Most of the South region of Brazil was classified as favorable (5), concentrating most of the yerba mate plantations across the continent. These regions produced 556,891 t in 2021 due to their ideal climate conditions (Fig. 3) (IBGE, 2021). Moreover, the Southeast region (4) and south of the Midwest region (3) showed climate favorability for yerba mate cultivation, being a possible alternative for these regions, which have no significant production.

Table 1. Area of the territory of each region classified for the yerba mate climatic zoning.

		Current (%)		
Number	**Region**	**Unfavorable**	**Favorable**	**Relatively favorable**
1	North	99,84	0,16	0,00
2	North East	92,85	0,27	6,88
3	Midwest	93,10	6,90	0,00
4	Southeast	41,21	46,85	11,94
5	South	2,77	96,75	0,48
6	Paraguay	79,88	20,12	0,00
7	Argentina	50,73	4,64	44,63
8	Uruguay	0,08	81,17	18,75
Total		**75,22**	**12,25**	**12,53**

Climate change during the first studied period (2021–2040) has already shown significant changes in the yerba mate climatic zoning for all scenarios (Fig. 4). The four SSP scenarios (2.6, 4.5, 6.0, and 8.5) presented reductions in areas classified as favorable throughout Brazil, representing about 12.25% of the national territory in the current scenario and, on average, only 8.5% (± 0.1) in the scenarios. Overall, 79.5% (± 0.2) of the studied area was classified as unfavorable in all scenarios (Table 2). All states with regions favorable for yerba mate cultivation in the current scenario showed an increase or the origin of limitations to cultivation, both thermal and hydric.

The Midwest region of Brazil (3) had only 0.1% (± 0.04) of areas favorable for yerba mate cultivation under all scenarios, which means a serious reduction compared to the current scenario (6.9%) (Fig. 4). Consequently, it may lead to economic losses, as the region is a major yerba mate consumer and has producing cities (WREGE et al., 2020). The Southeast region (4) showed a significant reduction in favorable areas, decreasing from 46.8–24.0% in SSP 5 8.5, a reduction of 48.6%. There was a higher reduction in the northernmost areas of the Southeast region (5), possibly due to an increase in the mean temperature, precluding the full yerba mate development (HOLOWATY; RAMALLO; SCHMALKO, 2012).

Table 2. Territory area of each region classified for the yerba mate climatic zoning during the period 2021–2040 for future scenarios.

		SSP 1 2.6 (%)		
Number	**Region**	**Unfavorable**	**Favorable**	**Relatively favorable**
1	North	100,0	0,0	0,0
2	North East	97,2	0,0	2,8
3	Midwest	99,8	0,2	0,0
4	Southeast	66,5	29,3	4,1
5	South	7,7	92,0	0,2
6	Paraguay	99,8	0,2	0,0
7	Argentina	49,1	3,1	47,7
8	Uruguay	0,0	90,0	10,0
Total		**79,2**	**8,8**	**12,0**
		SSP 2 4.5 (%)		
Number	**Region**	**Unfavorable**	**Favorable**	**Relatively favorable**
1	North	100,0	0,0	0,0
2	North East	97,3	0,0	2,7
3	Midwest	99,9	0,1	0,0
4	Southeast	68,1	26,5	5,4
5	South	8,0	91,8	0,2
6	Paraguay	99,8	0,2	0,0
7	Argentina	49,5	3,0	47,5
8	Uruguay	0,0	90,0	10,0
Total		**79,5**	**8,5**	**12,0**
		SSP 3 7.0 (%)		
Number	**Region**	**Unfavorable**	**Favorable**	**Relatively favorable**
1	North	100,0	0,0	0,0
2	North East	97,4	0,0	2,6
3	Midwest	99,9	0,1	0,0
4	Southeast	68,4	27,1	4,5
5	South	7,9	91,9	0,3
6	Paraguay	99,8	0,2	0,0
7	Argentina	49,0	3,2	47,8
8	Uruguay	0,0	90,0	10,0
Total		**79,4**	**8,6**	**12,0**
		SSP 5 8.5 (%)		
Number	**Region**	**Unfavorable**	**Favorable**	**Relatively favorable**
1	North	100,0	0,0	0,0
2	North East	97,6	0,0	2,4
3	Midwest	99,9	0,1	0,0
4	Southeast	70,9	24,0	5,1
5	South	8,5	91,1	0,3
6	Paraguay	99,9	0,1	0,0
7	Argentina	49,6	2,9	47,4
8	Uruguay	0,0	91,2	8,8
Total		**79,8**	**8,3**	**11,9**

Yerba mate (*Ilex paraguariensis*) zoning for climate change scenarios in 2081–2100 revealed a significant reduction in favorable areas relative to the current scenario (Fig. 5). The South (5) and

Southeast (4) regions stood out by showing a decrease in favorable areas, mainly in SSP 5 8.5, with a reduction of 49.4 and 45.9%, respectively (Table 3). It is possibly due to an increase in temperature in these regions, exceeding the ideal temperature limits for yerba mate cultivation, which compromises its development (MATSUNAGA; RAKOCEVIC; BRANCHER, 2014). It has a direct impact on the Brazilian production of yerba mate, considering that the South region of Brazil (5) is one of the main producers of this crop, in addition to being able to affect the regional economy (WALTER et al., 2022).
On the other hand, some regions presented a small increase in favorable areas for cultivation, such as in SSP 1 2.6, which had a 12.4% increase in the territory of Uruguay favorable for yerba mate (Fig. 5). This is due to the projected increase in temperature, which would be within the ideal range of 15 to 22°C for *Ilex paraguariensis* cultivation. However, the reduction in favorable areas for yerba mate is much more significant than the increase in favorable areas, especially in the RCP 8.5 scenario. This situation is worrying and requires urgent measures to avoid the possible projected climate change scenarios (BELLARD et al., 2012; WEBER, 2010) (Fig. 5).

Table 3. Territorial area of each region classified for the Yerba Mate climate zoning during the period 2081-2100 for future scenarios.

Number	Region	Unfavorable	Favorable	Relatively favorable
SSP 1 2.6 (%)				
1	North	100,0	0,0	0,0
2	North East	98,2	0,0	1,8
3	Midwest	100,0	0,0	0,0
4	Southeast	74,2	23,0	2,8
5	South	10,8	89,0	0,1
6	Paraguay	100,0	0,0	0,0
7	Argentina	49,5	2,6	47,9
8	Uruguay	0,0	93,6	6,4
Total		**80,2**	**8,0**	**11,7**
SSP 2 4.5 (%)				
1	North	100,0	0,0	0,0
2	North East	99,8	0,0	0,2
3	Midwest	100,0	0,0	0,0
4	Southeast	90,9	7,9	1,2
5	South	37,1	62,9	0,0
6	Paraguay	100,0	0,0	0,0
7	Argentina	55,7	0,8	43,5
8	Uruguay	2,5	92,5	5,0
Total		**84,5**	**5,2**	**10,3**
SSP 3 7.0 (%)				
1	North	100,0	0,0	0,0
2	North East	100,0	0,0	0,0
3	Midwest	100,0	0,0	0,0
4	Southeast	96,6	3,1	0,3
5	South	70,8	29,2	0,0
6	Paraguay	100,0	0,0	0,0
7	Argentina	56,0	1,4	42,6
8	Uruguay	23,9	74,0	2,1
Total		**86,9**	**3,1**	**10,0**
SSP 5 8.5 (%)				
1	North	100,0	0,0	0,0
2	North East	100,0	0,0	0,0
3	Midwest	100,0	0,0	0,0
4	Southeast	99,0	0,9	0,1
5	South	86,1	13,9	0,0
6	Paraguay	100,0	0,0	0,0
7	Argentina	56,1	3,5	40,5
8	Uruguay	52,1	47,4	0,5
Total		**88,3**	**2,2**	**9,5**

The dendrogram of the main Brazilian cities producing yerba mate shows a separation into two groups: one group represents the largest producers, while the other group represents the smallest yerba mate producers (Fig. 6). Analysis of the projection of favorability for yerba mate cultivation in SSP1 2.6, SSP2 4.5, SSP3 7.0, and SSP5 8.5 scenarios reveals a pattern regarding projected climate change and potential impact on yerba mate agriculture in Brazil (Fig. 6).

In the SSP1 2.6 scenario, both categories of cities, i.e., the largest (group 1) and smallest producers (group 2), maintain 100% favorability for yerba mate cultivation. This continuity of total favorability suggests that under conditions of low radiative forcing, growing conditions for yerba mate are likely to remain stable, similar to the results found by Wrege et al. (2020). The SSP2 4.5 scenario showed a slight decrease in favorability among the group of cities that produce less yerba mate (group 2), decreasing from 100 to 93%.

The SSP3 7.0 scenario projects a sharp drop in favorability, particularly for group 1 (95 to 54%), and a corresponding increase in unfavorable conditions for group 2 (5 to 47%). Most of the area becomes unfavorable for yerba mate cultivation in the most extreme scenario (SSP5 8.5). Only 15–17% of the areas remain favorable in group 1, while the unfavorability increases from 83 to 85% in group 2.

These results suggest that climate change, if not mitigated, could have significant effects on yerba mate production, with potentially severe impacts in cities that are currently less productive. It highlights the importance of climate change mitigation and adaptation strategies for the yerba mate industry (CROGE; CUQUEL; PINTRO, 2020).

Conclusion

Most future scenarios of climate change show a great impact on the climate due to the increase in the mean air temperature and the reduction in precipitation. It causes possible negative impacts on the yerba mate crop, with a total reduction of favorable areas in producing regions.

Most of the studied territory is classified as unfavorable for yerba mate cultivation, with only 12.25% (1.5 million km^2) considered favorable. The highest concentration of favorable areas is found in the South of Brazil and Uruguay, which are currently the main yerba mate producers. The yerba mate climate zoning showed significant changes during the studied period (2021–2040) in all analyzed scenarios, with a mean reduction of 8.55% (± 0.12) in areas classified as favorable throughout Brazil.

Projections for the period 2081–2100 showed an even more drastic decrease in areas suitable for yerba mate cultivation, especially in the South and Southeast regions of Brazil. On the other hand, a small increase in the favorability of yerba mate cultivation is observed in some regions, such as Uruguay, under less extreme climate change scenarios, such as SSP1 2.6.

Climate change impacts on yerba mate production are clear and varied according to the analyzed climate scenarios. Most of the areas in the most extreme scenario (SSP5 8.5) became unfavorable for yerba mate cultivation, especially in currently producing regions.

Declarations

Acknowledgments

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Figures

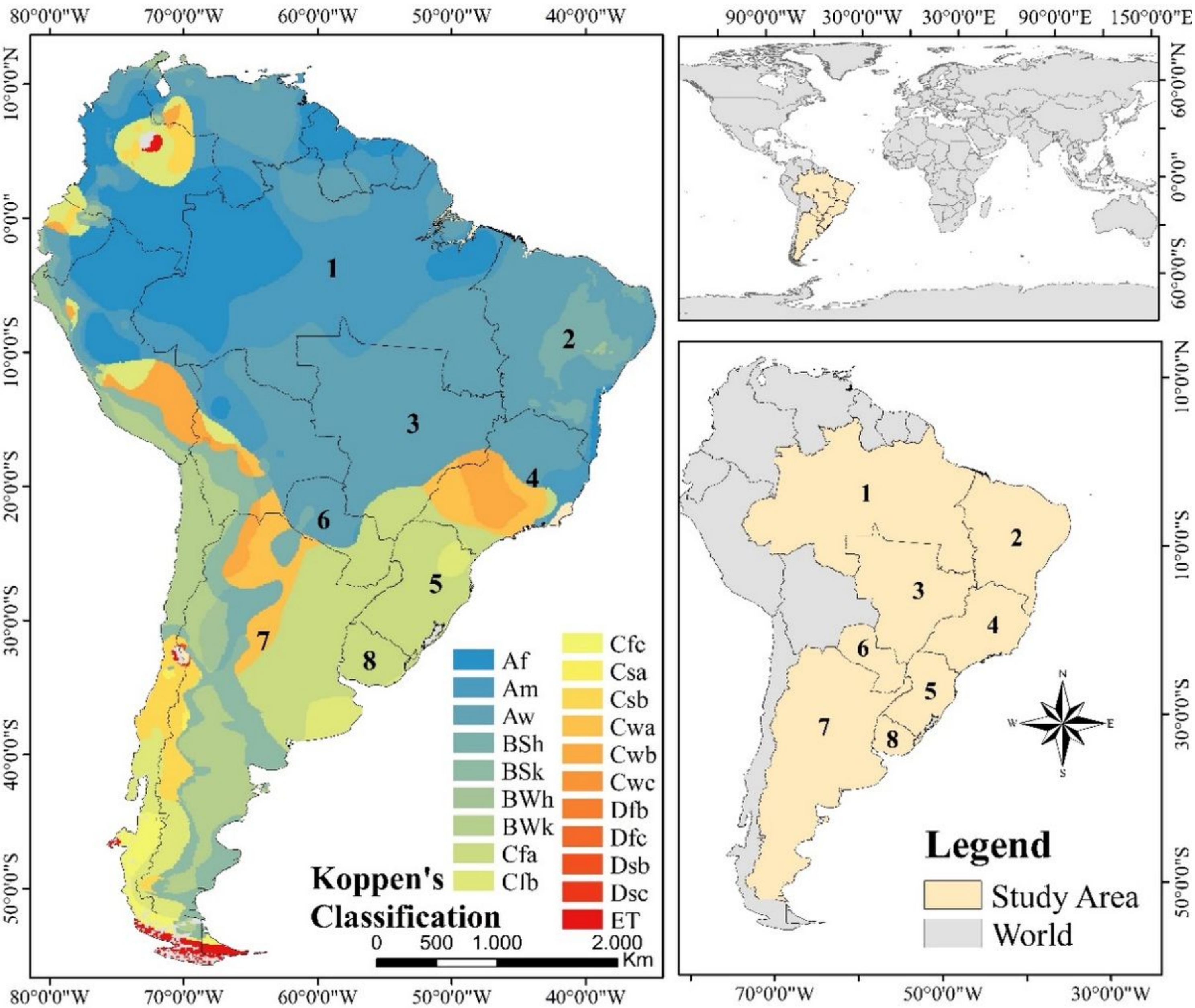

Figure 1

Location of the studied regions and the respective Köppen classification. 1 – North, 2 – Northeast, 3 – Midwest, 4 – Southeast, 5 – South, 6 – Paraguay, 7 – Argentina, and 8 – Uruguay.

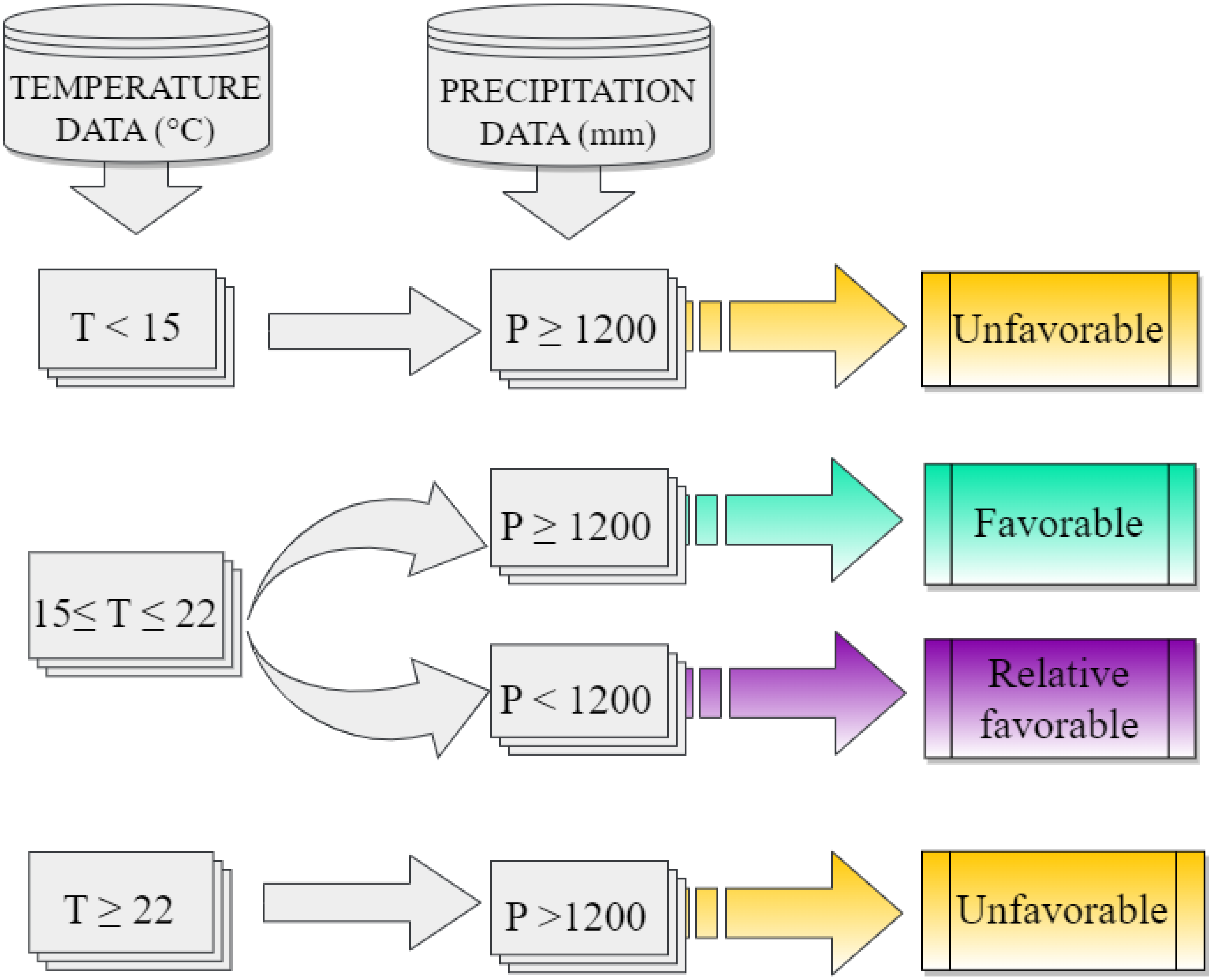

Figure 2

Climate favorability classes for yerba mate (*Ilex paraguariensis*).

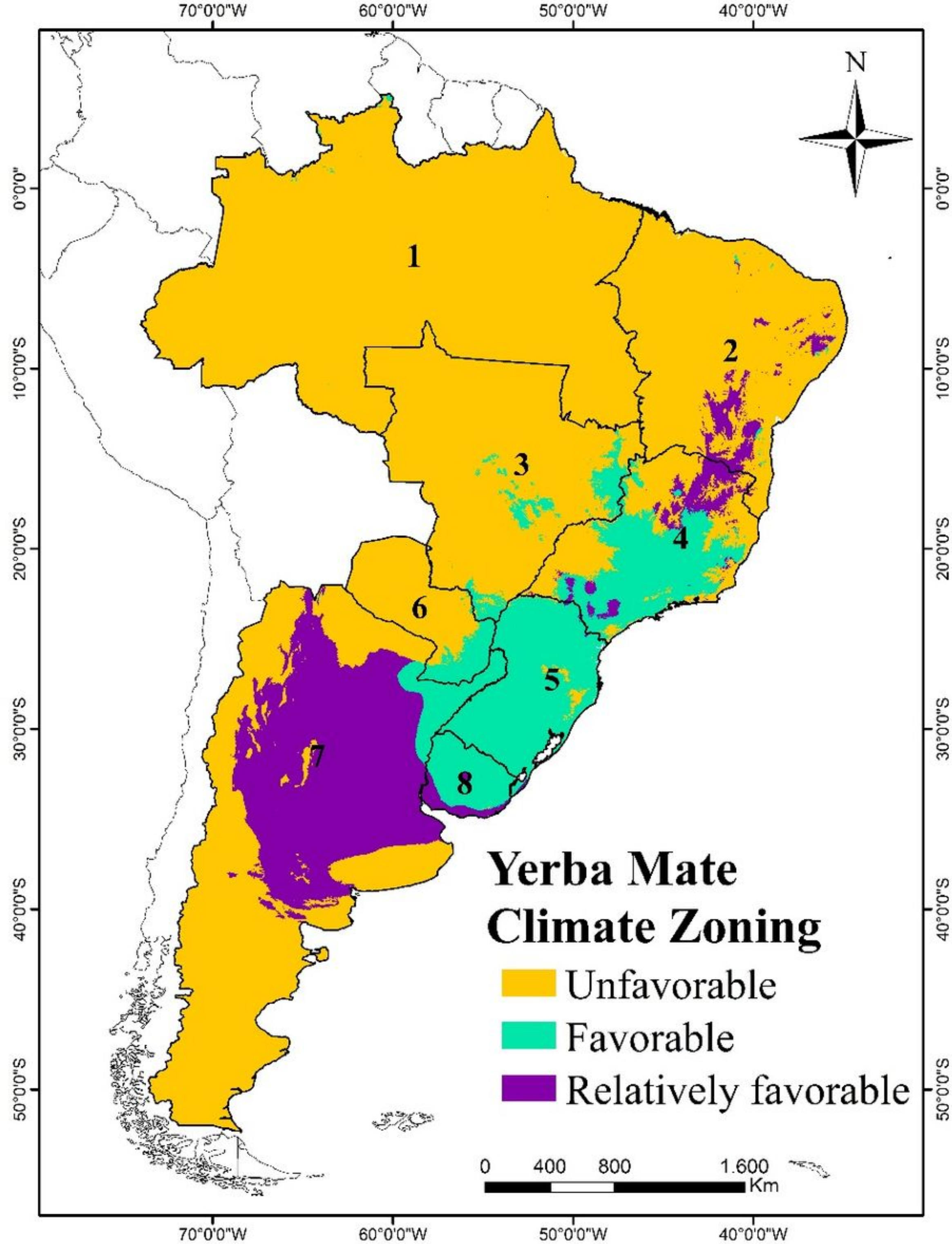

Figure 3

Yerba mate zoning during the current scenario in South American-producing regions.

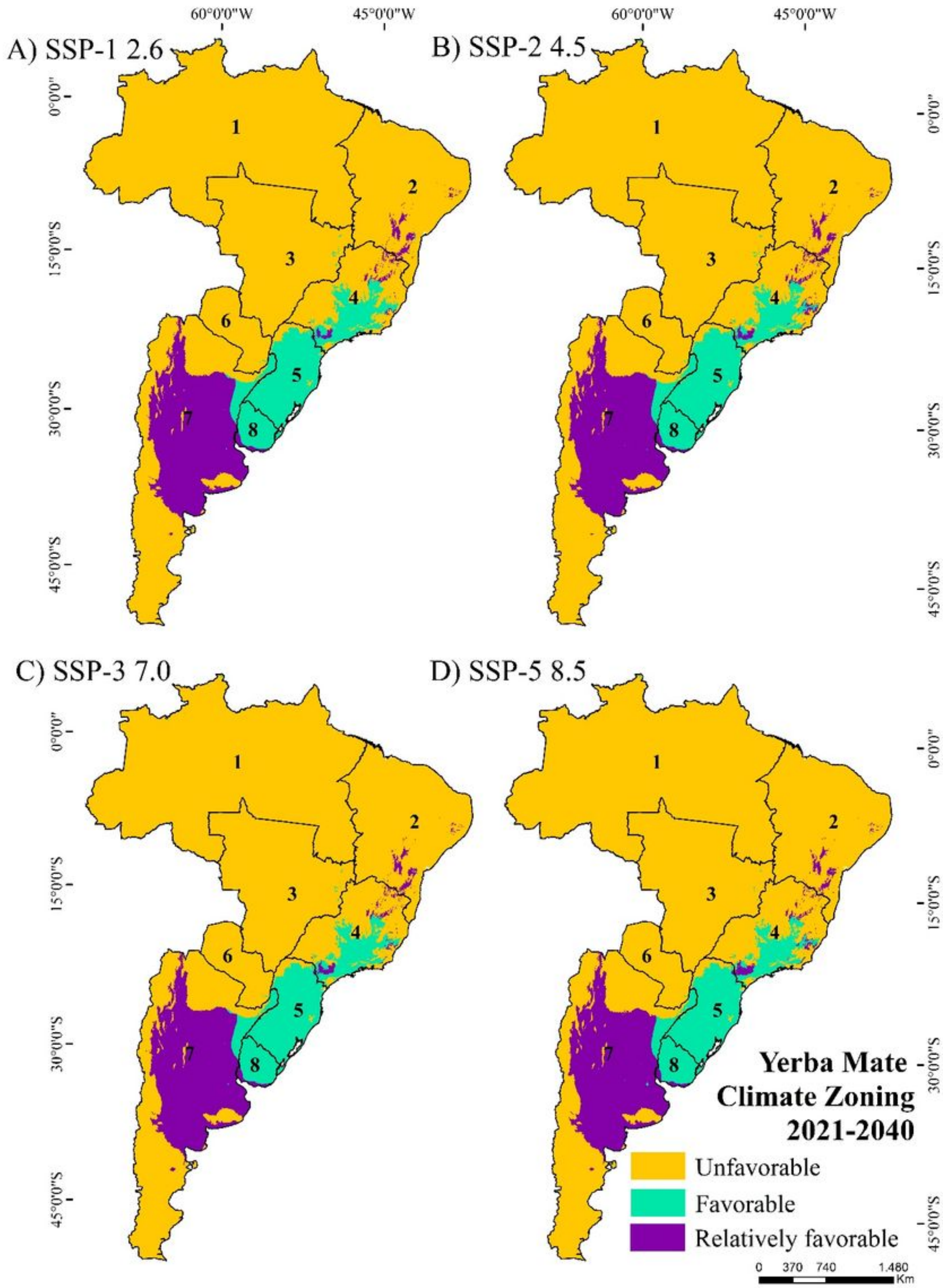

Figure 4

Yerba mate zoning during the period 2021–2040 in South American-producing regions. A) SSP-1 2.6 scenario, B) SSP-2 4.5 scenario, C) SSP-3 7.0 scenario, and D) SSP-5 8.5 scenario.

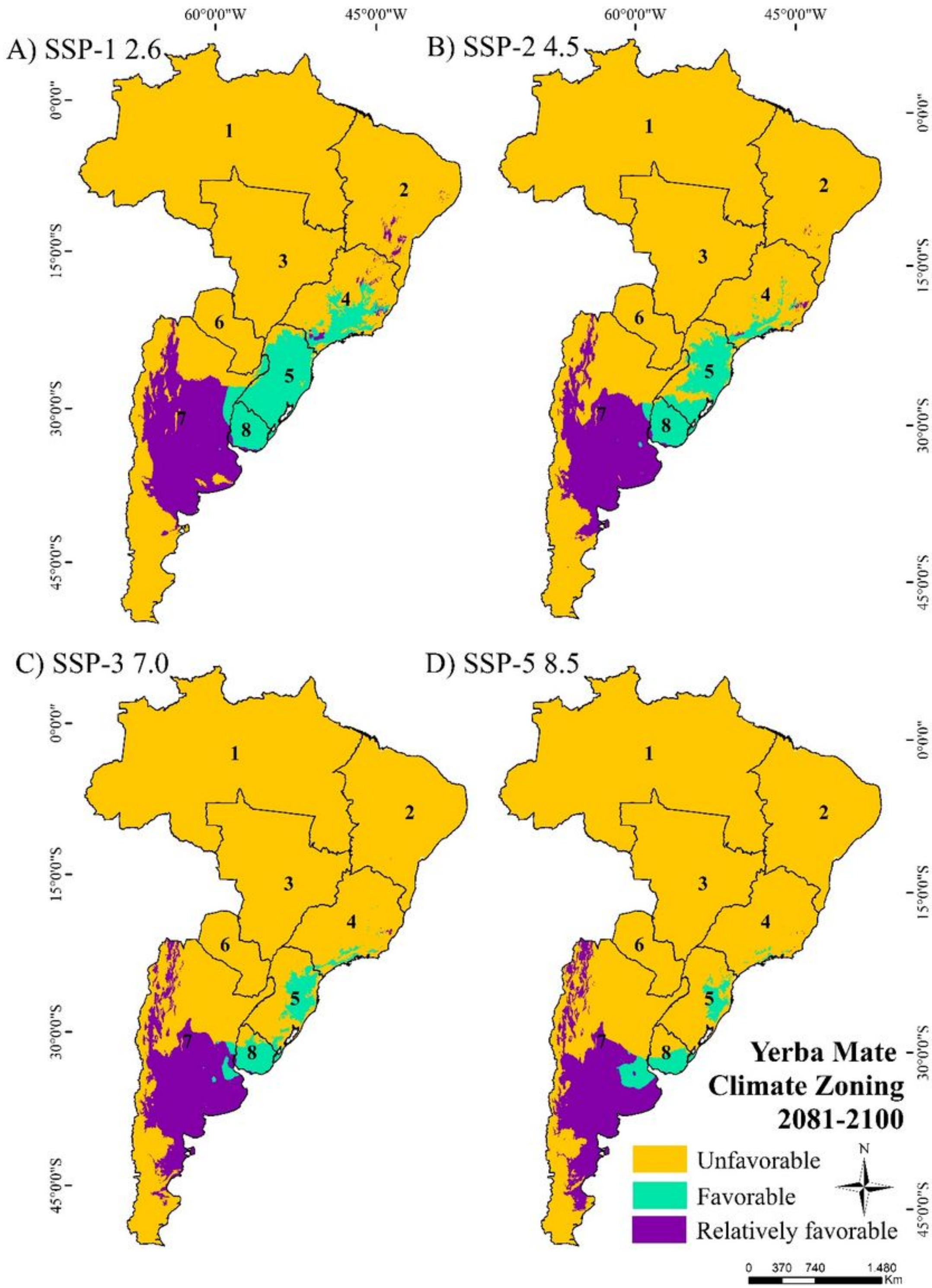

Figure 5

Yerba mate zoning during the period 2081–2100 in South American-producing regions. A) SSP-1 2.6 scenario, B) SSP-2 4.5 scenario, C) SSP-3 7.0 scenario, and D) SSP-5 8.5 scenario.

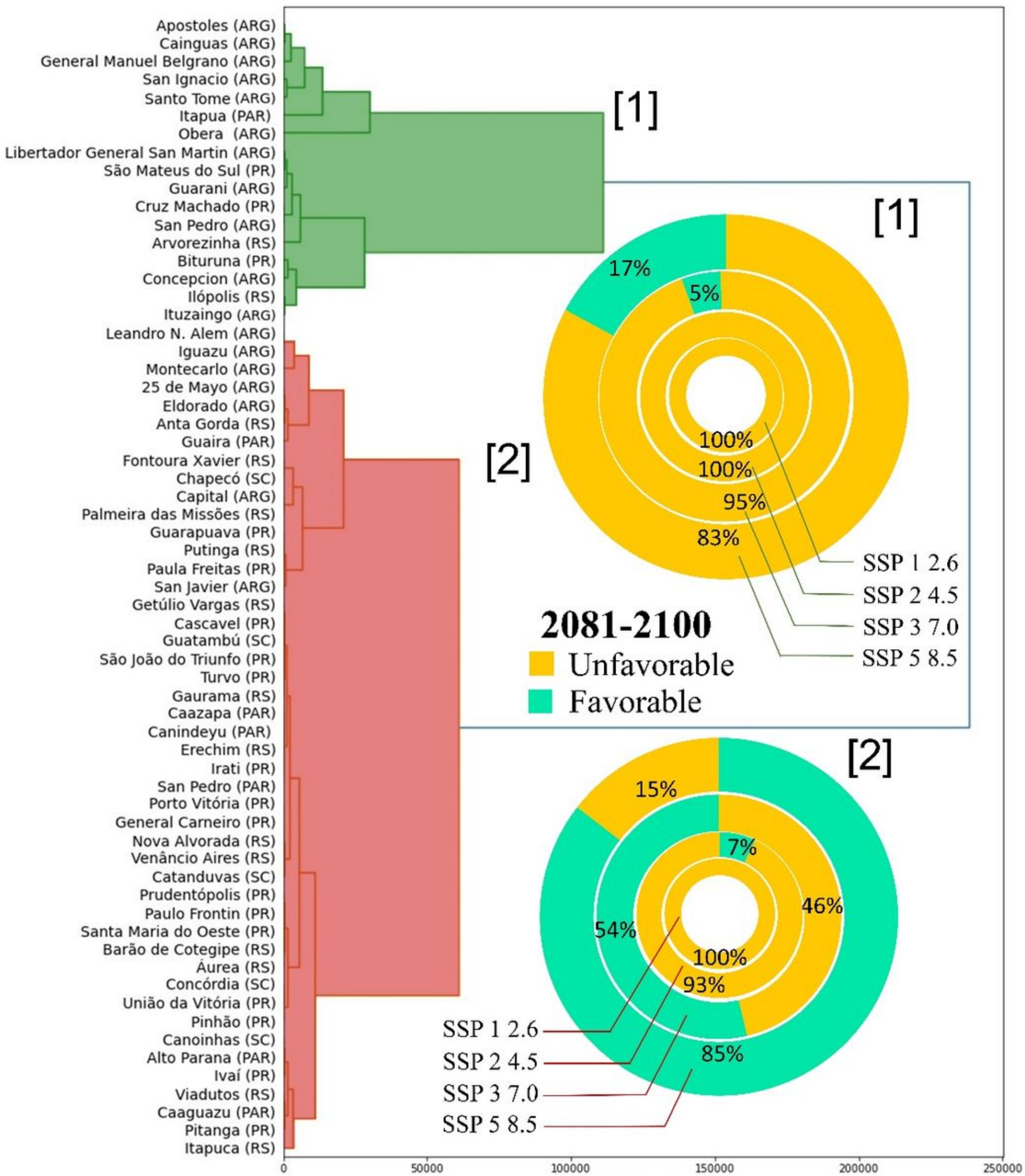

Figure 6

Dendrogram based on productivity data, representing the distribution of yerba mate-producing locations in Brazil and classification in future scenarios. Group of largest [1] and smallest [2] producers.