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Climatic Favorability to the Occurrence of *Hemileia vastatrix* in Apt Areas for the Cultivation of *Coffea arabica* L. in Brazil

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Abstract: In Brazil, coffee leaf rust (CLR), caused by the fungus *Hemileia vastatrix*, was first detected in *Coffea arabica* in January of 1970 in southern Bahia. Now widespread across all cultivation areas, the disease poses a significant threat to coffee production, causing losses of 30–50%. In this context, the objective of this study was to identify and quantify the different classes of occurrence of CLR in areas apt and restricted to the cultivation of Arabica coffee in Brazil for a more informed decision regarding the cultivar to be implanted. The areas of climatic aptitude for Arabica coffee were defined, and then, the climatic favorability for the occurrence of CLR in these areas was evaluated based on climatic data from TerraClimate from 1992 to 2021. The apt areas, apt with some type of irrigation, restricted, and with some type of restriction for the cultivation of Arabica coffee add up to 16.34% of the Brazilian territory. Within this 16.34% of the area of the Brazilian territory, the class of climatic favorability for the occurrence of CLR with greater representation is the favorable one. Currently, the disease is controlled with the use of protective and systemic fungicides, including copper, triazoles, and strobilurins, which must be applied following decision rules that vary according to the risk scenario, and according to the use of resistant cultivars. This study provides a basis for choosing the most suitable cultivars for each region based on the degree of CLR resistance.

Keywords: agricultural zoning; cultivar selection; coffee leaf rust; coffee

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1. Introduction

Coffee is one of the world's leading beverages and the second most traded commodity, trailing only oil [1]. This crop is cultivated in more than 70 countries, with Brazil being the leading producer and exporter, responsible for one third of global coffee production [2,3]. Two species dominate worldwide production: *Coffea arabica* and *Coffea canephora*. *Coffea arabica* is favored for its sweeter taste, whereas *Coffea canephora* is noted for its high caffeine content [4].

Since *Coffea arabica* requires a specific climate for development and production within relatively narrow limits, the crop yield and quality will be below viable as the climatic conditions deviate from the ideal [5,6]. Climatic zoning of coffee cultivation is extremely important for both the implementation and planning of agricultural activities. Delimiting regions climatically means not only establishing indicators of the physical and biological production potential but also planning for areas apt for production, taking into account pre-existing natural resources [7,8].

The most devastating disease affecting coffee plantations is coffee leaf rust (CLR), caused by the fungus *Hemileia vastatrix* [9]. In Brazil, CLR was first identified in *Coffea arabica* in January 1970, in the southern region of Bahia, and only four months later the disease was already present in almost all coffee plantations in the country [10]. Currently, the disease can be found in practically all regions where Arabica (*Coffea arabica*) and robusta (*Coffea canephora*) coffees are cultivated. Coffee leaf rust epidemics, with greater intensities than previously observed, have affected several countries, including Colombia from 2008 to 2011, Central America and Mexico in 2012–2013, and Peru and Ecuador in 2013 [11].

The biology of *H. vastatrix* involves the production of uredospores, which are spread by wind and rain, infecting the leaves of the coffee plant [12]. The fungus thrives in warm, humid environments, making its ecology closely tied to tropical and subtropical regions. Symptoms of CLR include yellow-orange lesions on the underside of the leaves, leading to defoliation and reduced photosynthetic capacity, ultimately affecting coffee yield and quality. The pathogen disrupts the plant's physiology by impairing nutrient and water transport. In optimal conditions, CLR can undergo multiple life cycles, with up to eight generations per year, making it a persistent threat to coffee cultivation [13].

In coffee-producing regions of Brazil, coffee leaf rust can reduce productivity by 30 to 50%, depending on the resistance level of the genotype [14]. In Brazil, the primary control methods include the application of systemic fungicides, such as copper, triazoles, and strobilurins, applied either according to a fixed schedule or based on disease monitoring [15,16]. Additionally, the use of resistant cultivars and cultural practices are also commonly employed [17]. However, there are disadvantages to the application of copper fungicides. These fungicides may increase the abundance of coffee leaf miners and mites, as these organisms can thrive when fungicides reduce competition or eliminate natural predators [18], and concerns about their effects on human health [17]. The development of varieties with durable genetic resistance to the variability in coffee leaf rust pathogenicity becomes prominent for disease control [19].

With the purpose of providing decision support for diagnosis, planning, and management, studies on areas favorable to the occurrence of coffee leaf rust, correlated with classes of aptitude for cultivation, become essential and justifiable for the strategic establishment of disease mitigation and management. Considering the importance of wide spread of this pathogen, this study hypothesizes that, in areas apt for coffee cultivation in Brazil, there are different classes of favorability for the occurrence of CLR, and by identifying these classes, it aims to provide a basis for choosing the best cultivars to be implemented in each region, aiming to mitigate possible productive and economic losses.

2. Materials and Methods

2.1. Study Area

This study was conducted in Brazil (Figure 1), which covers an area of approximately 8,510,295 km^2 with an estimated population of 215 million inhabitants [20]. Besides being a country with significant physical characteristics and natural resources, Brazil is also one of the world's largest exporters of agricultural products, an economic activity strongly influenced by the climate and extreme weather conditions.

Due to its vast territorial extent, the precipitation regime in Brazil is modulated by various atmospheric systems [21]. Therefore, the climates of Brazil vary according to their location, and much of the country lies within the Intertropical Climate Zone, an area between the Tropics of Cancer and Capricorn.

The extreme south of Brazil is part of the Southern Temperate Climate Zone, between the Tropic of Capricorn and the Antarctic Circle [22,23]. The climates of Brazil are classified into the following: equatorial, tropical, highland tropical, semi-arid, subtropical, and Atlantic tropical [24,25].

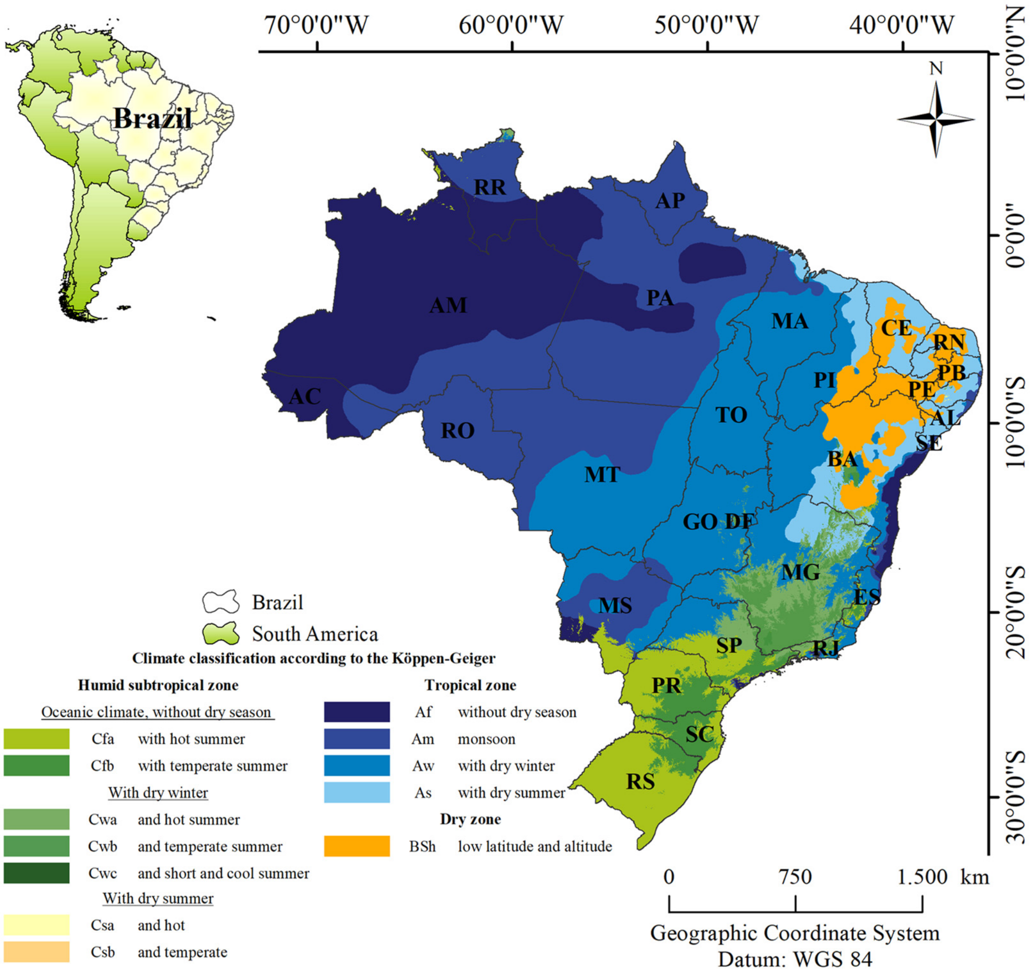

Figure 1. Study area. Source: Adapted from [25].

2.2. Database

The methodological flowchart containing the necessary steps for the acquisition of the database, described in this subsection, is presented in Figure 2.

The meteorological data required for the development of the climatic zoning of Arabica coffee and for the climatic favorability to the occurrence of coffee leaf rust were acquired from the climatology laboratory, TerraClimate.

TerraClimate consists of monthly climate data and the climatic water balance for the global land surface. These data provide important inputs for ecological and hydrological studies on a global scale that require high spatial resolution and time-variable data. All data have a monthly temporal resolution and a spatial resolution of approximately 4 km^2 [26].

In this study, we analyzed the variables of maximum temperature (°C), minimum temperature (°C), vapor pressure (kPa), and water deficit (mm) over a 30-year period (1992 to 2021). The data, available in compressed NetCDF format with monthly records, were inserted into a GIS environment, where each band corresponds to a specific month. Working with data spanning three decades resulted in a total of 360 bands for each variable.

For the calculation of thermal variables, the maximum temperature was determined by the average of the monthly maximums, while the minimum temperature was calculated from the average of the monthly minimums. The mean temperature was then obtained by averaging the maximum and minimum temperatures. As for vapor pressure and water deficit, both were calculated using the annual cumulative average. This methodological approach provides a detailed and accurate view of the climatic conditions over the studied period.

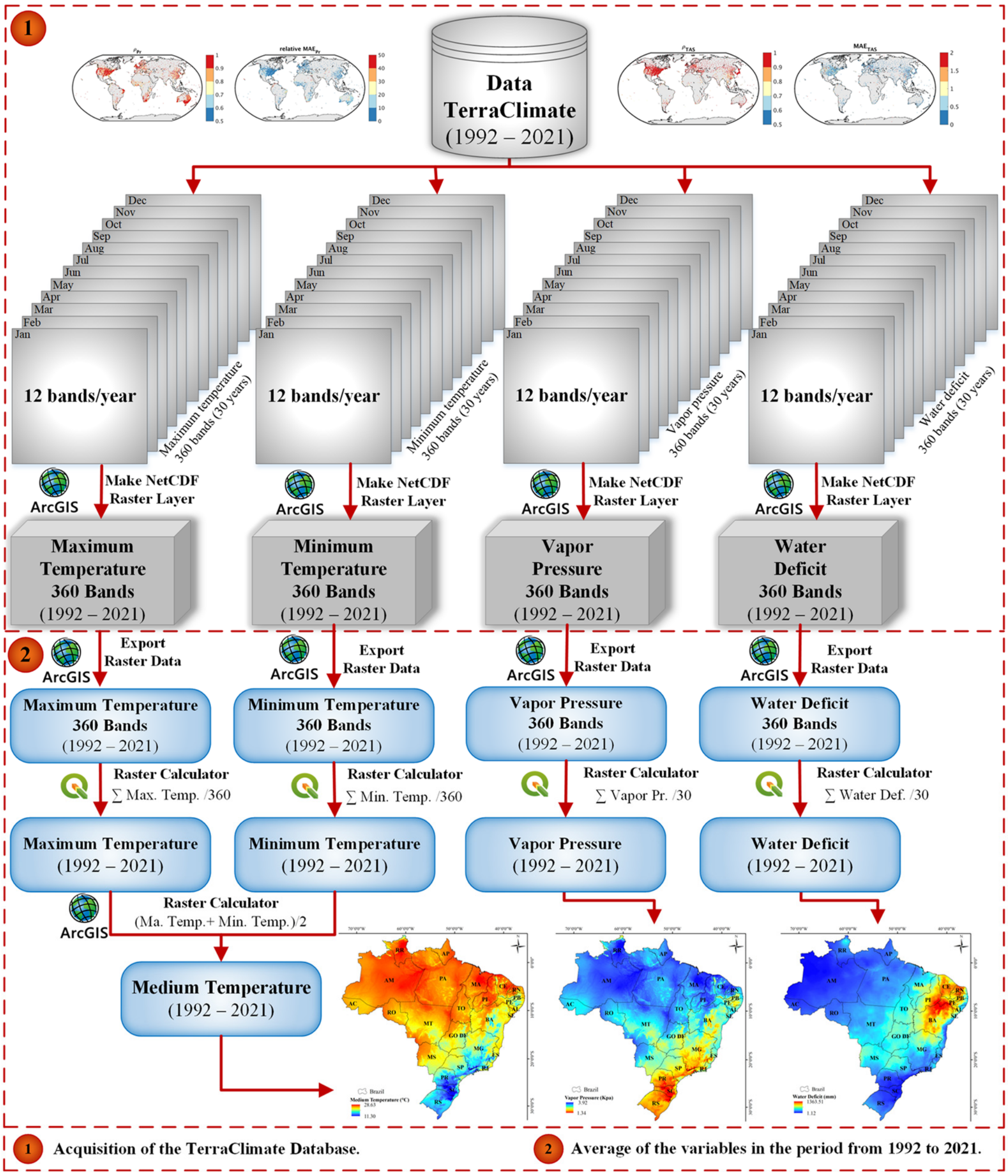

Figure 2. Methodological steps for obtaining meteorological data from TerraClimate.

2.3. Climatic Zoning

The methodological flowchart containing the necessary steps for the climatic zoning for Arabica coffee is presented in Figure 3 and was based on the methodology proposed by [27], using the ArcGIS® software.

Stage 1: Climatic zoning for Arabica coffee

After acquiring the raster images of average temperature and annual water deficiency, we began processing the data using the ArcGIS® software. Initially, the images were projected using the "Project Raster" function. Subsequently, the "Raster to Point" function was applied to convert the raster file into a vector format and perform interpolation using the "Interpolation (IDW)" function, resulting in a raster file with 1 km^2 cells.

Once the images were projected and had a resolution of 1 km^2, the "Reclassify" function was applied. This step was based on the values of each variable, leading to the generation of reclassified raster images that identify areas with aptitude, restriction, and inaptitude classes for Arabica coffee cultivation in Brazil, as detailed in Tables 1 and 2.

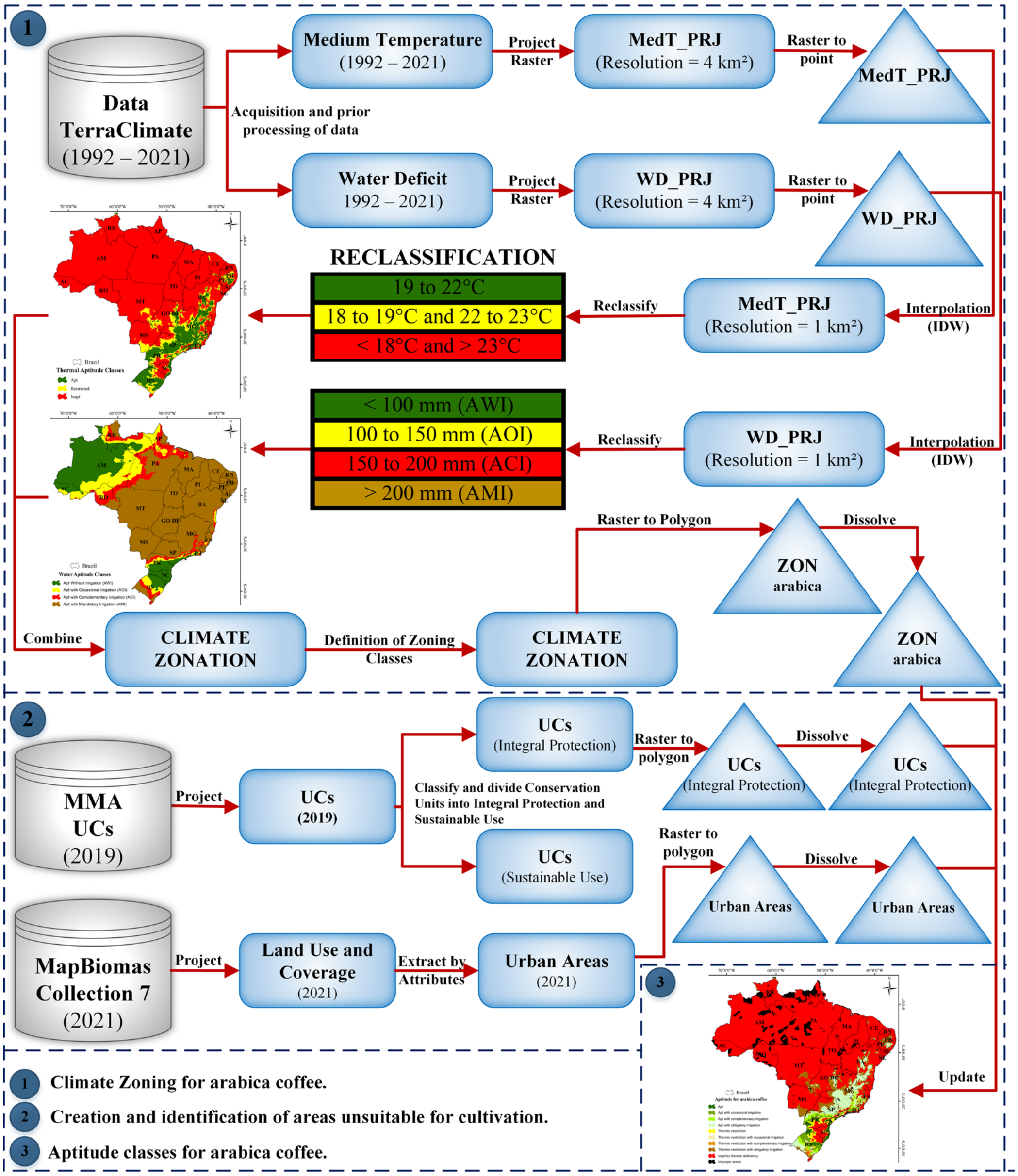

Figure 3. Methodological steps used for the development of the climatic zoning of Arabica coffee (*Coffea arabica* L.) in Brazil, where MedT_PRJ is projected average temperature, WD_PRJ is projected water deficit, MMA refers to the Ministry of the Environment, UCs refers to Conservation Units, and ZON is climatic zoning.

Table 1. Thermal aptitude ranges for Arabica coffee crops (*Coffea arabica* L.).

Aptitude Classes	Temperature (°C)
Apt	19 to 22
Restricted	18 to 19 or 22 to 23
Inapt	<18 or >23

Source: Adapted from [27].

Table 2. Water deficiency ranges for Arabica coffee cultivation (*Coffea arabica* L.).

Aptitude Classes	Water Deficiency (mm)
Apt without irrigation (AWI)	<100
Apt with occasional irrigation (AWOI)	100 to 150
Apt with complementary irrigation (AWCI)	150 to 200
Apt with obligatory irrigation (AWMI)	>200

Source: Adapted from [27].

After generating the reclassified matrices of average temperature and water deficit based on aptitude classes, the "Combine" function was used to generate the climatic zoning for Arabica coffee cultivation in Brazil, considering these two variables. A column named "class" was created, where names representing the degrees of aptitude, restriction, and inaptitude were inserted according to the interaction between temperature and water deficit variables, respecting the most restrictive classification.

The representative raster image of the climatic zoning for Arabica coffee was converted to polygonal vector format using the "Raster to Polygon" function. Due to the high number of polygons obtained after the vector conversion process, the "Dissolve" function was applied, resulting in a new vector file with an attribute table containing the aptitude classes.

In the attribute table of the dissolved polygonal vector file, three new fields were created, with real data types, named area, perimeter, and percentage. In editing mode, using the "Calculate Geometry" function, areas (in km^2) and perimeters (in km) were calculated for the respective aptitude classes.

Finally, through the "Field Calculator" function, the percentage of aptitude classes was calculated, resulting in climatic zoning maps for Arabica coffee cultivation in Brazil.

Stage 2: Creation and identification of areas apt for cultivation

Some areas of the Brazilian territory are inappropriate for agricultural cultivation, particularly highlighting the integral protection conservation units and urban areas within the Brazilian territory. With this in mind, the conservation units (UCs) obtained from the Ministry of the Environment (MMA) [28] and land use and land cover data were downloaded to extract urban areas, obtained from MapBiomas for the year 2021 [29].

After acquiring the raster image concerning the conservation units, they were projected and reclassified according to their category into integral protection conservation units and sustainable use conservation units. According to Law Nº 9985/2000, the basic objective of integral protection conservation units is to preserve nature, allowing only indirect use of their natural resources.

According to the definition of UCs categories, integral protection conservation units do not allow direct use of their resources and consequently agricultural cultivation. Therefore, the integral protection conservation units were exported, then converted into a vector file using the "Raster to Polygon" function in ArcGIS® and projected. Due to the high number of polygons obtained after the vector conversion process, the "Dissolve" function was applied, resulting in a new vector file with an attribute table, where a column was inserted to classify inapt areas.

With the raster file of land use and land cover for the year 2021 in hand, the "Project" function was used to project the image. Then, the "Extract by Attributes" function was utilized to extract urban areas from the raster image, forming a new raster file. The urban areas were converted from raster to vector format using the "Raster to Polygon" function, projected, and the "Dissolve" function was applied to the vector file. This resulted in a new vector file with an attribute table where a column was inserted, and in this column, the class of inapt areas was included.

Stage 3: Aptitude classes for Arabica coffee

The "Update" function was used to overlay the inapt areas, coming from the full protection conservation units and urban areas, on the climatic zoning of Arabica coffee. In this way, the map of climatic zoning for Arabica coffee cultivation was generated.

In the attribute table of the polygonal vector file, three new fields were created, with real data types, titled area, perimeter, and percentage. In editing mode, using the "Calculate Geometry" function, the areas (km^2) and perimeters (km) for the mentioned aptitude classes were calculated, and through the "Field Calculator" function, the percentage of the aptitude classes was calculated, culminating in the climatic zoning maps for Arabica coffee cultivation in Brazil.

2.4. Climatic Favorability for the Occurrence of Coffee Leaf Rust

In this topic, the methodology was based on the structuring of a climatic database for the variables considered important for the establishment and development of coffee leaf rust: average air temperature and relative humidity.

The climatic data for average air temperature were obtained according to item 2.2 of this methodology, and the average air humidity was calculated based on the average air temperature and vapor pressure obtained in accordance with item 2.2.

There is a limit to the amount of vapor that a given volume of air can support, and when this limit is reached, the air is said to be saturated. The factor that determines the saturation state of water vapor in the atmosphere is solely the temperature. Therefore, the maximum vapor pressure is a function of the air temperature; the higher the temperature, the greater its capacity to support moisture, and consequently, the greater the pressure exerted by the water vapor [30].

When the air is saturated, the pressure exerted by the water vapor is called the maximum water vapor pressure (e_s) and, as it is a function of temperature, it can be calculated using Equation (1) proposed by Tetens [31]. To calculate the maximum water vapor pressure, we use the "Raster Calculator" function of ArcGIS® where we enter Equation (1), using the average air temperature obtained from TerraClimate.

$$e_s = 0.611 * 10^{[(7.5 * T_{ar})/(237.3 + T_{ar})]} \quad (1)$$

where e_s is the maximum water vapor pressure (kpa) and T_{ar} is the air temperature (°C).

Since the relative humidity of the air is the ratio, in percentage, between the amount of water vapor the air contains and the maximum amount it could contain at the same temperature, we use the "Raster Calculator" function of ArcGIS® where we enter Equation (2) to obtain the relative humidity.

$$UR = \frac{e_a}{e_s} * 100 \quad (2)$$

where UR is the relative humidity of the air (%); e_a is the current water vapor pressure (kpa); and e_s is the maximum water vapor pressure (kpa).

With the matrix images of temperature and relative humidity in the ArcGIS® computational application, they were projected using the "Project Raster" function. Then, the "Raster to Point" function was employed to convert the matrix file into a vector and interpolate it using the "Interpolation (IDW)" function, generating a matrix file with 1 km^2 cells. Subsequently, climate favorability maps for coffee leaf rust development were elaborated, adapting the methodology used by [32]). The "Reclassify" function was applied based on the classes from Table 3, aiming to generate the reclassified matrix image of temperature and relative humidity for coffee leaf rust occurrence in Brazil. These classes were defined based on epidemiological data on the effect of average temperature and relative humidity on coffee leaf rust development. The boundaries of the disease's climate favorability classes were established based on bibliographic reports [33–35].

Table 3. Favorability classes for coffee leaf rust occurrence based on average temperature and relative humidity intervals.

Class	Temperature (°C)	Relative Humidity (%)
Highly favorable	21 to 24	>82
Favorable	18 to 21 or 24 to 27	75 to 82
Relatively favorable	15 to 18 or 27 to 30	70 to 75
Unfavorable	<15 or >30	<70

Source: Adapted from [35].

After generating the reclassified average temperature and relative humidity matrices based on favorability classes, the "Combine" function was used to create a map showing the spatial distribution of coffee leaf rust. A column named "class" was created, where names referring to the degrees of favorability and unfavorability were inserted based on the interaction between temperature and relative humidity variables.

The raster image of the spatial distribution of favorability for coffee leaf rust occurrence was converted to polygon vector format using the "Raster to Polygon" function. Due to the high number of polygons obtained after the vector conversion process, the "Dissolve" function was applied, resulting in a new vector file with an attribute table containing favorability classes for CLR occurrence.

In the attribute table of the dissolved vector file, three new fields were created, with real data types, titled area, perimeter, and percentage. In editing mode, the "Calculate Geometry" function was used to calculate the area (km^2) and perimeter (km) for the respective favorability classes. Finally, using the "Field Calculator" function, the percentage of favorability classes was calculated, resulting in the climatic favorability map for coffee leaf rust occurrence in Brazil.

2.5. Climatic Favorability for the Occurrence of Coffee Leaf Rust in Appropriate Areas for Arabica Coffee Cultivation

As the objective of this study was to assess the favorability for the occurrence of coffee leaf rust in areas climatically apt for Arabica coffee cultivation in Brazil, a cut on the favorability of CLR occurrence concerning areas apt and restricted for Arabica coffee cultivation was performed using the "Clip" function of ArcGIS®.

3. Results

The climatic zoning for Arabica coffee in Brazil is presented in Figure 4A. According to the results, it is observed that areas apt and apt with some type of irrigation for the cultivation of Arabica coffee make up 9.30% of the Brazilian territory (Figure 4A). Meanwhile, the restricted areas and those with some type of restriction for the cultivation of Arabica coffee total 7.04%, the inapt areas correspond to 77.01% of the Brazilian territory, and the improper areas make up 6.65% of the Brazilian territory. Included in the category of inappropriate areas are those belonging to fully protected conservation units and urban areas.

Excluding the areas inapt due to thermal deficiency and the areas inappropriate for the cultivation of Arabica coffee, we have an area of 1,390,729.56 km^2, which is equivalent to 16.34% of the Brazilian territory; it is worth noting that areas with some types of restriction are included in this total (Figure 4A).

The percentage of Brazilian territory occupied by the climate favorability classes "highly favorable" and "favorable" for coffee leaf rust, considering the period from 1992 to 2021, is 1.34% and 25.07%, respectively (Figure 4B).

Considering only the areas that are apt, apt with irrigation, restricted, and with some type of restriction for the cultivation of Arabica coffee, we have the following: 54,088.66 km^2 of highly favorable area, 502,160.58 km^2 of favorable area, 89,759.17 km^2 of area favorable due to temperature, 290,145.52 km^2 of area favorable due to humidity, 423,427.28 km^2 of relatively favorable area due to humidity, and 31,148.35 km^2 of area unfavorable due to humidity for the development of coffee leaf rust (Figure 5A,B).

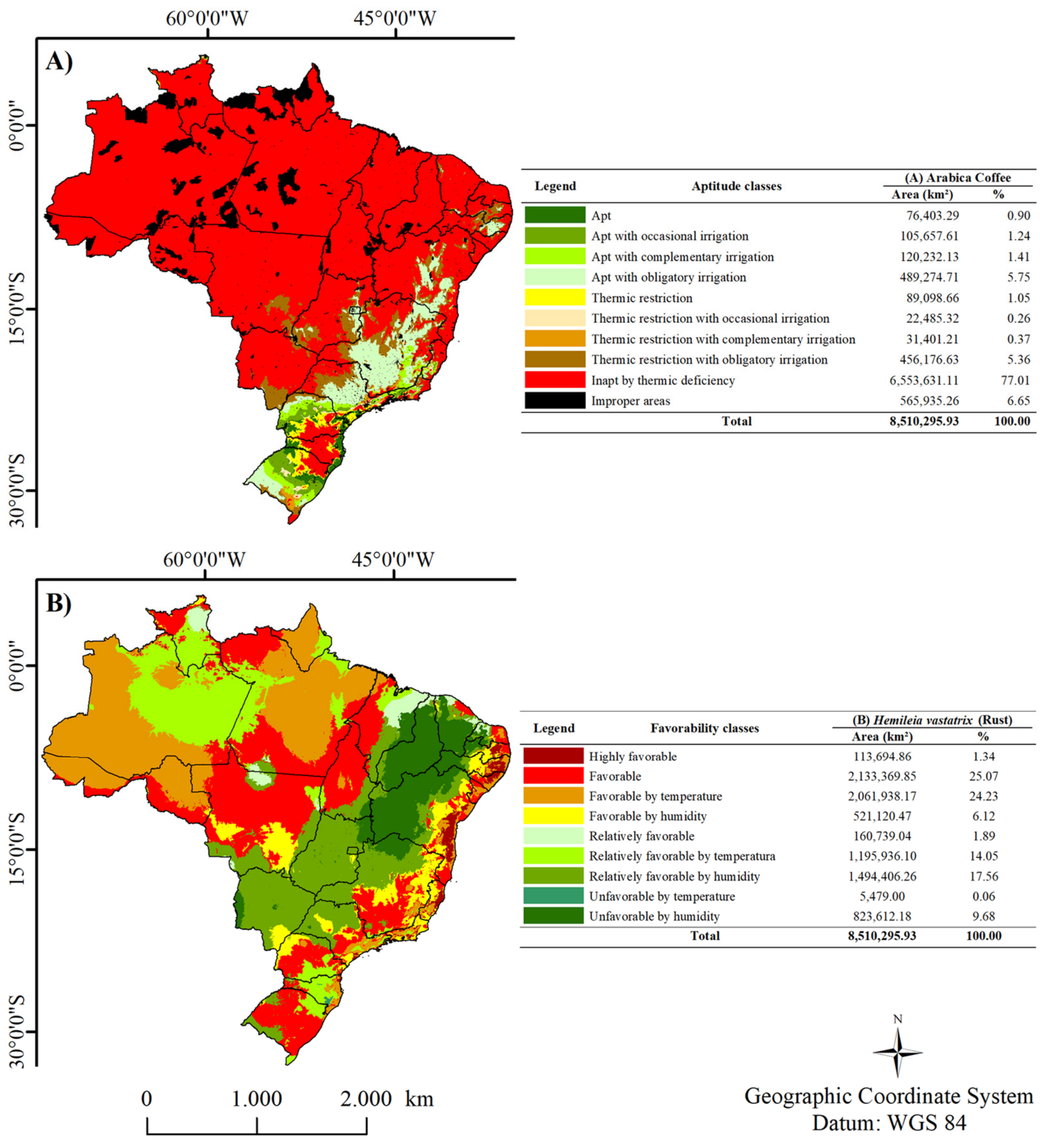

Figure 4. (**A**) Climatic zoning for Arabica coffee; (**B**) favorability for the occurrence of coffee leaf rust.

After removing the areas inapt and improper for the cultivation of Arabica coffee, it is observed that the area with the highest percentage of occupancy for the favorability of coffee leaf rust is the favorable class for the occurrence of coffee leaf rust (Figure 5B), and within this favorability class (favorable), the class with the largest area is apt with obligatory irrigation, 35.42% or 177,842.53 km^2 of area, followed by the class apt with occasional irrigation, which represents 16.72% of the area equivalent to 83,977.44 km^2 (Figure 5C).

It can be observed in Figure 5C that the favorable class and the favorable by temperature class in relation to the occurrence of coffee leaf rust have more than 50% of their area apt or apt with some type of irrigation for the cultivation of Arabica coffee.

When analyzing the percentage of area occupied by each favorability class for the occurrence of coffee leaf rust, within the aptitude classes for the cultivation of Arabica coffee, it is noted that the class occupying the largest area is the favorable one, with the only exception being the thermal restriction class with obligatory irrigation. In this aptitude class, the relatively favorable class due to humidity stands out, occupying 53.65% of the area, which is equivalent to 244,756.48 km^2 (Figure 6).

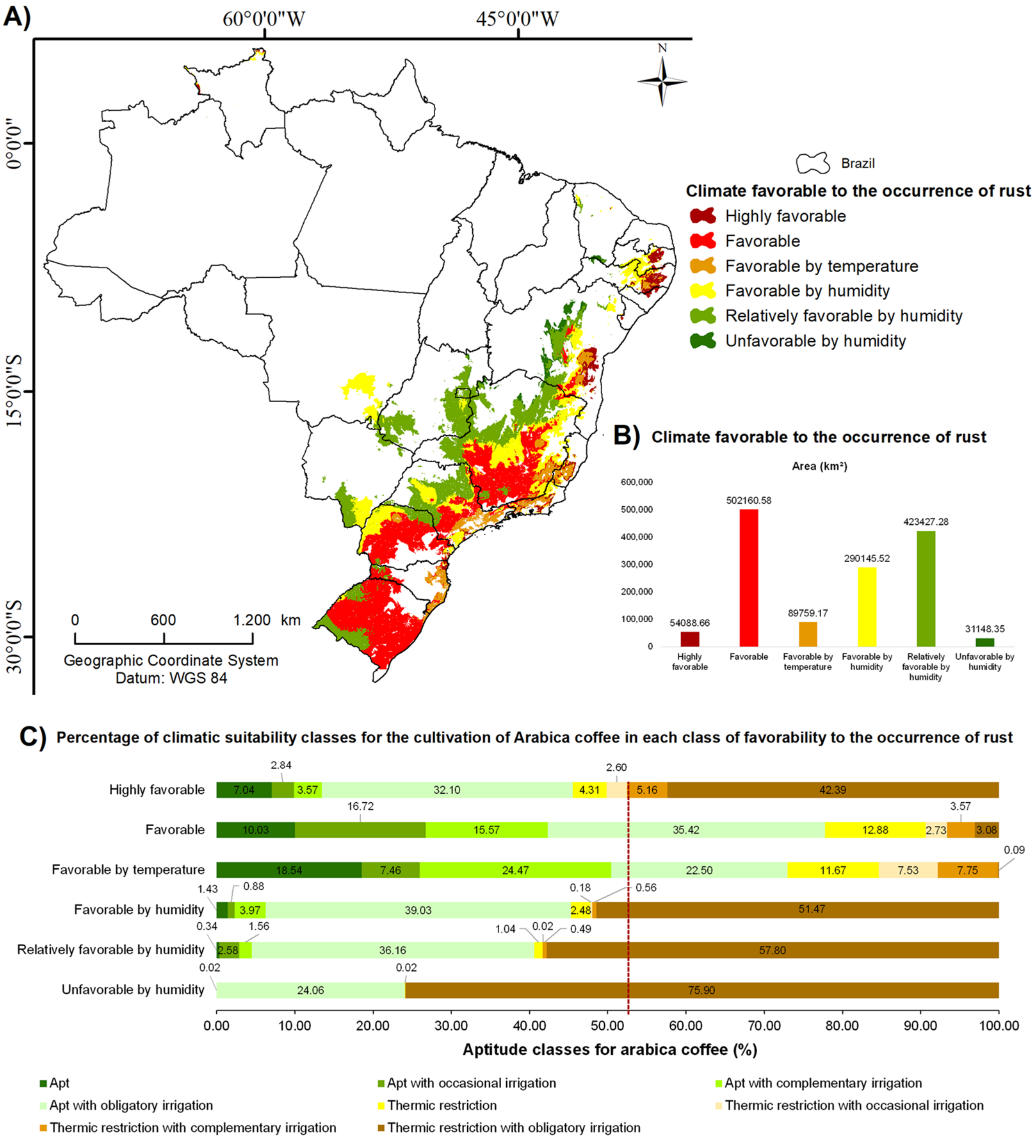

Figure 5. (**A**) Favorability for the occurrence of coffee leaf rust in areas apt and restricted for the cultivation of Arabica coffee; (**B**) areas of the favorability classes for the occurrence of coffee leaf rust; (**C**) percentage of Arabica coffee aptitude classes in each favorability class for the occurrence of coffee leaf rust.

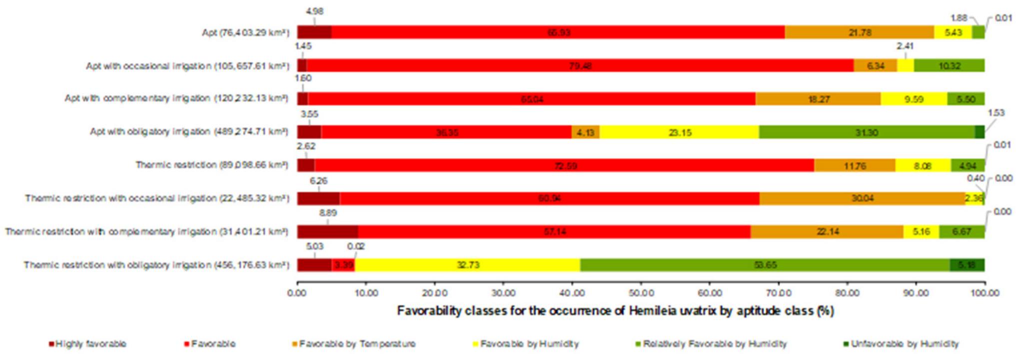

Figure 6. Favorability classes for the occurrence of coffee leaf rust by aptitude class (%).

In Table 4, the areas related to the favorability classes for the occurrence of coffee leaf rust can be observed for Brazilian states with areas apt, apt with some type of irrigation, restricted, and with some type of restriction for the cultivation of Arabica coffee. It is noted that the states of Minas Gerais, Rio Grande do Sul, and São Paulo have the largest favorable areas for the occurrence of coffee leaf rust, with 391,919.32 km^2, 237,735.89 km^2, and 163,972.69 km^2 of area, respectively.

Table 4. Favorable areas for the occurrence of coffee leaf rust (km^2), in states that are apt, apt with irrigation, restricted, and with some type of restriction for the cultivation of Arabica coffee.

State	Highly Favorable	Favorable	Favorable by Temperature	Favorable by Humidity	Relatively Favorable by Humidity	Unfavorable by Humidity	Total
Alagoas	2367.13	-	17.56	213.24	-	-	2597.93
Amazonas	19.39	0.05	0.72	8.33	-	-	28.48
Bahia	14,704.09	11,531.87	10,028.28	28,135.92	38,107.19	21,632.06	124,139.42
Ceará	60.57	-	-	1474.83	1848.32	2083.33	5467.06
Distrito Federal	-	-	-	56.02	4468.05	-	4524.06
Espírito Santo	3669.33	658.05	8008.22	4607.05	2.53	-	16,945.18
Goiás	-	1.00	-	3396.91	86,793.97	1162.45	91,354.32
Mato Grosso	-	-	-	32,269.93	3264.31	-	35,534.24
Mato Grosso do Sul	-	-	-	19,452.29	30,839.18	-	50,291.47
Minas Gerais	2181.20	144,040.96	16,386.30	95,046.88	129,383.37	4880.62	391,919.32
Paraíba	7392.91	99.30	29.49	11,070.60	200.48	-	18,792.79
Paraná	895.94	93,983.09	3355.89	31,427.33	17,411.14	8.00	147,081.38
Pernambuco	12,222.21	614.32	4017.48	15,039.85	509.49	1367.73	33,771.08
Piauí	-	-	-	-	-	9.16	9.16
Rio de Janeiro	4975.37	2910.88	8730.11	6965.91	7.55	-	23,589.81
Rio Grande do Norte	2.00	-	-	333.79	1.00	-	336.79
Rio Grande do Sul	-	192,536.31	1621.55	1781.04	41,796.99	-	237,735.89
Roraima	1562.38	16.34	10.34	3172.13	-	-	4761.20
Santa Catarina	1620.60	13,138.41	18,349.12	331.94	3897.63	4.00	37,341.71
São Paulo	2050.53	42,629.99	19,204.12	35,305.36	64,781.68	1.00	163,972.69
Sergipe	365.02	-	-	56.16	-	-	421.17
Tocantins	-	-	-	-	114.38	-	114.38
Total	54,088.66	502,160.58	89,759.17	290,145.52	423,427.28	31,148.35	1,390,729.56

4. Discussion

Coffee plants are sensitive to climate, soil conditions, and agricultural practices, as described in the literature by variables such as altitude, temperature, precipitation, air humidity, pH in water, cation exchange capacity, organic carbon content of the soil, and soil density and texture [36–38]. From this list, we excluded altitude for our model, which is typically associated with climatic conditions, such as temperature and atmospheric pressure; due to this high correlation we opted to exclude altitude and use temperature [24,30]. Another variable used in this study was the water deficit, which is directly related to precipitation. The other variables related to the chemical conditions of the soil can be altered through agricultural practices and were not used for zoning.

For the temperature, we compiled their optimal (apt), suboptimal (restricted), and inadequate (inapt) levels for coffee production (Table 1). Annual average temperatures of 19 °C to 22 °C are considered ideal for coffee production [27,39]. Temperatures above this range accelerate the ripening of the coffee pulp before the grain reaches full maturation, consequently decreasing coffee quality [38,40]. Additionally, plant growth is reduced, and vegetative abnormalities begin to occur at very low or very high temperatures [41].

For water deficit, [27] estimated that water needs should not exceed 100 mm/year for the cultivation of Arabica coffee without the need for irrigation. However, high water levels can lead to waterlogging, increased fungal diseases, premature berry drop, and ineffective fertilizer application, among other issues [42].

The results regarding the climatic aptitude zones for the cultivation of Arabica coffee show that 1,390,729.56 km^2 of the total area of the Brazilian territory, which is equivalent to 16.34% of the territory, are apt and restricted areas for the cultivation of Arabica coffee. This value is higher than the current estimated cultivation area (2022), which is 1.81 million hectares corresponding to 18,100 km^2 [43]. These figures demonstrate the potential for production and expansion of Arabica coffee-producing areas in Brazil.

According to [44], Latin America, and especially Brazil, is the region on the planet with the best remaining potential for agricultural expansion, due to the abundance of land, water, and biodiversity. However, it is important to note that although agricultural growth generates undeniable economic gains for the Brazilian trade balance, environmental impacts can also be substantial if growth is not based on planning and strong use of technologies that seek sustainable production. Environmental damage can also lead to economic and social losses that are often underestimated.

According to [45], the area of the Atlantic Forest coverage, one of the main biomes where coffee cultivation occurs, as well as biodiversity, have been decreasing at a rapid pace in recent decades, a concerning scenario for one of the global biodiversity hotspots (*hotspots* represent the natural areas of planet Earth that have a high ecological diversity).

The Arabica coffee-producing states are as follows: Minas Gerais, São Paulo, Espírito Santo, Bahia, Paraná, Rio de Janeiro, Goiás, Amazonas, Ceará, Pernambuco, Mato Grosso do Sul, and the Federal District [46]. All these states have areas classified as apt, apt with irrigation, or apt with some type of restriction, according to this study. However, states such as Alagoas, Mato Grosso, Paraíba, Rio Grande do Sul, Roraima, Santa Catarina, Piauí, Rio Grande do Norte, Sergipe, and Tocantins (Figure 4A) have areas classified in this study as potentially apt for coffee cultivation, which contrasts with CONAB data regarding the producing states. Among the mentioned states, Piauí, Rio Grande do Norte, Sergipe, and Tocantins have areas with some type of restriction for the cultivation of Arabica coffee of negligible size and do not have the class apt for the cultivation of Arabica coffee.

Each of the areas identified as apt, apt with irrigation, or apt with some type of restriction should be closely analyzed for proper planning and implementation of Arabica coffee cultivation. Some of these regions may have specific conditions that prevent cultivation, such as frequent frost occurrences, rocky terrain, conservation areas, or legal reserves, and these environmental and physical obstacles must be considered. On the other hand, regions with thermal restrictions can have their production potential increased through temperature reduction by implementing an agroforestry system that provides shading and modifies the microclimate [47]. In this case, it is advisable to choose varieties of Arabica coffee that are more adapted to development in shaded conditions.

The study developed by [48] demonstrated that the shaded cultivation of the varieties Catuaí Amarelo IAC 86, Tupi IAC 1669-33, and Obatã IAC 1669-20 achieved an average productivity that was higher (Catuaí Amarelo) or statistically the same (Tupi and Obatã) compared to the cultivation of the same varieties in full sun. Thus, we have a database that can be compiled and cross-referenced to choose the best variety according to local characteristics and the producer's desires.

Regarding the results of favorability for the occurrence of coffee leaf rust, it is noted that the classes of favorable and favorable by temperature are the ones with the largest extent, 2,133,369.85 km^2 and 2,061,938.17 km^2, respectively (Figure 4B). This scenario undergoes a slight change when areas inapt and improper for the cultivation of Arabica coffee are removed, highlighting at the level of area the classes of favorable (502,160.58 km^2) and relatively favorable by humidity (423,427.28 km^2), as observed in Figure 5B. This occurs because areas inapt by temperature for the cultivation of Arabica coffee (temperature below 18 °C and above 24 °C) show similarity with part of the areas favorable to the development of coffee leaf rust (temperature between 18 °C and 21 °C and between 24 °C and 27 °C), and areas with temperature between 24 °C and 27 °C are thermally inapt for the cultivation of Arabica coffee and favorable to the development of coffee leaf rust.

Within the areas that are apt, apt with some type of irrigation, and restricted, we will only have the classes of highly favorable and favorable for the occurrence of coffee leaf rust in relation to temperature (Figure 5C).

Coffee leaf rust is the most devastating disease that attacks coffee plantations [9]. In high incidences, coffee leaf rust can cause defoliation of up to 50% and yield losses between 30 and 50% [14]. The distribution of favorability for the occurrence of coffee leaf rust across the states apt and restricted for the cultivation of Arabica coffee, as seen in Figure 5A and Table 4, shows that the largest areas correspond to the favorable class and that the states with the largest areas in relation to this class are Rio Grande do Sul (192,536.31 km^2) and Minas Gerais (144,040.96 km^2). Coffee plantations are not very common in the lands of Rio Grande do Sul, but research indicates that climate changes in recent years may cause a new geography of production, making way for crops previously restricted to other areas of Brazil [49].

Sugar cane and coffee plantations, for example, have the potential to compete with traditional crops in the landscape of the state of Rio Grande do Sul in the face of climate change. However, currently, adverse climatic phenomena are obstacles to coffee production in the southern region of Brazil. The occurrence of frost in Brazil is predominantly observed at latitudes greater than 20° S, covering the states of São Paulo, Mato Grosso do Sul, Minas Gerais, Paraná, Santa Catarina, and Rio Grande do Sul, with the latter being the most affected [50].

In the classes of areas apt, apt with occasional irrigation, and apt with supplementary irrigation, more than 50% of the areas are highly favorable and favorable to the occurrence of coffee leaf rust, while the areas apt with obligatory irrigation have 3.55% and 36.35% of the area highly favorable and favorable to the development of coffee leaf rust, respectively (Figure 6). Such information, when correlated with the spatial distribution of the data, provides a basis for choosing the best variety of coffee to be planted in each region (Figure 5A and Table 4).

Among the available varieties, the most planted are Mundo Novo and Catuaí, both susceptible to coffee leaf rust. There has been a gradual introduction of new materials, mainly those resistant to coffee leaf rust, where the cultivars Catucaí, IBC-Palma, Acauã, and the Sarchimores (Tupi, Obatã, and IAPAR 59) stand out, as well as those more recently launched, such as Oeiras, Catiguá, Araponga, Paraíso, Pau-Brasil, and Arara [51,52].

In areas identified as highly favorable and favorable for the occurrence of coffee leaf rust and that require irrigation, it is recommended to adopt varieties resistant to coffee leaf rust and tolerant to drought, such as Acauã. The Acauã cultivar originates from the cross between Mundo Novo IAC 388-17 and Sarchimor (IAC 1668), and it shows good drought tolerance, good quality beverage, late cycle, and is highly resistant to coffee leaf rust [51]. Besides Acauã, Arara has gained prominence and is being planted in most coffee-growing regions; it comes from a natural hybridization between Obatã and Catuaí Amarelo and is highly resistant to coffee leaf rust with high productivity and potential for a good-quality beverage [53].

In some cases, it can be associated with resistant varieties, or it may be necessary to use other forms of CLR management involving various integrated approaches to keep the disease under control. Monitoring the incidence of CLR allows for more efficient and rational use of fungicides, keeping infection levels below 5% throughout the season with a relatively low number of sprayings (4–6) per season. The timing of these applications is crucial for successful control, particularly in susceptible varieties. Additionally, improving agronomic practices such as weed control, fertilization, and pruning enhances plant health, allowing coffee plants to better withstand CLR attacks [16]. These strategies collectively contribute to effective CLR management and sustained coffee production.

In areas with thermal restrictions due to higher temperatures, cultivars such as Catuaí (adapted to extreme temperatures—both high and low), IBC-Palma, and Acauã, which are well adapted to warm regions, should be chosen [51]. If these areas are highly favorable, favorable, favorable by temperature, or favorable by humidity, it is recommended to plant cultivars resistant to coffee leaf rust, among which the most recommended would be the Acauã cultivar.

If the region is relatively favorable by humidity or unfavorable by humidity, it is recommended to plant varieties resistant to high temperatures, but not necessarily resistant to coffee leaf rust; cultivars such as IBC-Palma 1 or IBC-Palma 2, which are moderately resistant, or Catuaí, which is susceptible to coffee leaf rust occurrence, could be used.

It is also important to correlate the results of this study with the management practices to be adopted. Organic or agroforestry cultivation enables the creation of a microclimate and consequently reduces temperature [47], being especially recommended for areas with thermal restrictions and that may be affected by frosts. Cultivars such as Araponga MG1, Catiguá MG1, Catiguá MG2, Catiguá MG3, Paraíso MG H 419-1, Pau-Brasil MG1, and SACRAMENTO MG 1 are recommended for cultivation in organic and/or agroforestry systems and are highly resistant to coffee leaf rust [51,53].

5. Conclusions

Despite research advances, coffee leaf rust remains a significant threat and increases the production costs in the country's coffee agriculture. This situation arises from a combination of favorable environmental conditions in most coffee regions and the extensive use of susceptible varieties.

This study's results show variability in the spatial distribution of climatic favorability for coffee leaf rust occurrence in Brazil. The correlation between the aptitude and favorability classes provides a foundation for selecting the most appropriate cultivars for each region. Moreover, the management practices to be adopted must be considered.

Minas Gerais, the largest producer of Arabica coffee, has the most extensive area classified as highly favorable and conducive to coffee leaf rust. This necessitates special attention in selecting cultivars to be planted. In regions such as southeastern Minas Gerais, which are classified as highly favorable and conducive to the occurrence of coffee leaf rust, it is essential to consider the desired planting objectives (e.g., productivity) and prioritize resistant cultivars like Arara and Acauã Novo. Additionally, it is extremely important to monitor the incidence of CLR for more efficient and rational use of fungicides, keeping infection levels below 5% throughout the season with a relatively low number of sprayings.

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