Agroclimatic Zoning for the Incidence of Brown Eye Spot on Coffee Under Climate Change Scenarios

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Abstract

Brown eye spot (*Cercospora coffeicola*) is one of the main fungal diseases of coffee, leading to a significant drop in crop productivity and beverage quality in Brazil. This study aimed to elaborate an agroclimatic zoning for the incidence of brown eye spot on coffee under climate change scenarios, as suggested by IPCC (IPCC-AR5), in the main coffee-growing regions. Climate data of air temperature, precipitation, and relative humidity were collected from the National Aeronautics and Space Administration/Prediction of Worldwide Energy Resources – NASA/POWER platform from 1989 to 2020 for 46 municipalities in the states of Paraná, São Paulo, Minas Gerais, Espírito Santo, Goiás, and Bahia. The ideal climate for brown eye spot occurrence consists of an air temperature (T_{mean}) between 18 and 30 °C, relative humidity (RH_{mean}) > 90%, and leaf wetness duration (LWD) > 9 hours. The number of hours of leaf wetness was determined by the sum of hours with relative humidity > 90%. Relative humidity was estimated for each hour of the day using estimated data of mean dew point temperature, maximum relative humidity, minimum relative humidity, and air temperature. Climate change scenarios were designed based on sets of climate simulations for the 21st century. Scenario S1 is the current scenario without changes, while scenarios S2 and S3 show $T_{\text{mean}} + 1.5$ °C and 3.0 °C, respectively, with RH_{mean} without changes. Scenarios S4 and S5 present RH_{mean} varying from –30% to +30%, respectively, with T_{mean} unchanged. In the current scenario (S1), Minas Gerais presented a predominance of 100% for low climate risk to brown eye spot in September. Paraná presented a medium risk in 76.15% of the state in April. Scenarios S2 and S3 showed significant changes, increasing the average fitness class in the study region, mainly in the states of São Paulo, Minas Gerais, Rio de Janeiro, and Paraná. Scenario S4 showed 100% predominance of the low-risk class. In contrast, S5 showed the occurrence of the high-risk class for the study region with a +30% increase in relative humidity. The state of Minas Gerais presented a predominance of the high-risk class for the development of *C. coffeicola* in 76, 100, 97.83, 89.3, 93.46, 80.64, and 57.77% from November to May, respectively. The presence of high relative humidity represents the main factor for the expansion of the high-risk class for the development of *C. coffeicola*.

Introduction

Coffee is a beverage that has been gaining more consumers over the years, with its production being expanded and quality improved (FERRÃO et al., 2019). It is a commodity of great importance in the global market, with a large share in the generation of employment in many countries (VEGRO, ALMEIDA, 2020). Among the 124 listed coffee species, Arabian coffee (*Coffea arabica* L.) and robusta coffee (*Coffea canephora* P.) are responsible for almost all the coffee consumed in the world (DAVIS et al., 2011).

In Brazil, coffee is grown on more than 2 million hectares (HINNAH et al., 2018), representing a strategic commodity for its economy (SOUZA et al., 2011), standing out as the world's largest producer and exporter of Arabian coffee (SILVA et al., 2019). Currently, Brazilian coffee production is 63,077 bags of coffee, with emphasis on the states of Minas Gerais (34,647) and Espírito Santo (13,958) as the largest producers (CONAB, 2020).

Coffee production can be affected by many factors, especially diseases, including brown eye spot, caused by the fungus *Cercospora coffeicola*. The fungus attacks from the planting of seedlings in the nursery to the field (VALE et al., 2020), leading to production losses ranging from 15 to 30% and beverage quality reduction (AZEVEDO DE PAULA et al., 2016). In addition to coffee, fungi of the genus *Cercospora* cause leaf spots on several crops such as corn, beet, rice, banana, and soybean (GUNASINGHE, YOU, BARBETTI, 2016).

Growth, sporulation, and germination of fungi are influenced by environmental variables (SILVA et al., 2016), mainly agrometeorological elements such as air temperature, relative humidity, and leaf wetness duration since changes in the microclimate favor the increased incidence of diseases (PAIVA et al., 2013). Leaf wetness duration is defined as the time of accumulation of water on the plant tissue surface (SHIN, PARK, KIM, 2021) and is directly related to the rate of infection and pathogen development (JIAN et al., 2020).

The development of *C. coffeicola* is more favored with air temperatures between 17 and 22 °C (ZAMBOLIM et al., 2005), associated with relative humidity above 90% (VALE et al., 2019). In addition, factors such as rainfall periods followed by dry spells or intense solar radiation and water deficit may favor the occurrence of brown eye spot (PATRICIO and OLIVEIRA, 2013). The main symptoms are lesions on leaves and fruits, characterized by yellowish halos surrounded by brown and necrotic rings with light-colored spots in the center (SOUZA et al., 2015; BOTELHO et al., 2019; PEREIRA et al., 2019), resulting in defoliation and decreased productivity and coffee quality (MARTINS, MAFFIA, MIZUBUTI, 2008; BOTELHO et al., 2017). The disease causes premature drop and emptying of the attacked fruits (COSTA et al., 2011), being more frequent when they are close to the ripening period (FERNANDES, VIEIRA JUNIOR, 2015). *Cercospora* spp. fungi produce a photoactive toxin called cercosporin, responsible for destroying host cell membranes (SOUZA, HERRERO, DAUB, 2019).

Brown eye spot is commonly controlled with the use of fungicides and nutritional management, as the disease benefits from nitrogen and calcium deficiency and potassium excess (PATRICIO and OLIVEIRA, 2013). In addition, the development of disease-tolerant or resistant coffee cultivars is important to reduce production costs and increase productivity (PEREIRA et al., 2019). Recurrent losses occur in coffee plantations due to the difficulties reported in the control and prevention of the disease (BELAN et al., 2015; WALLER, 1985).

Climate changes can lead to increases or decreases in the occurrence of brown eye spot in coffee plantations depending on the Brazilian region. In this sense, evaluating the projections of the Intergovernmental Panel on Climate Change (IPCC), created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) (HULME, 2016), is fundamental to carry out periodic assessments of scientific knowledge on climate change (MINX et al., 2017). Reports containing emission scenarios based on variable thermal indices and changes in the concentration of greenhouse gases are issued periodically (IPCC, 2014). The fifth IPCC report (AR5)

showed an increase of 0.85 °C in the mean air temperature since 1880 over land areas (O'NEILL et al., 2016).

Climate change is a phenomenon that includes rising atmospheric CO₂, higher temperatures, more severe droughts, and more frequent storms (JACTEL, KORICHEVA, CASTAGNEYROL, 2019). Climate changes will have far-reaching impacts on agricultural, livestock, and fisheries production, altering the prevalence of agricultural pests and diseases (CAMPBELL et al., 2016; DURAND-BESSART et al., 2020). Agricultural productivity can be affected directly and indirectly through impacts on crop diseases (NEWBERY, QI, FITT, 2018). A reduction of 1 to 5% in global agricultural production has been estimated per decade over the last 30 years, which is related to climate variations (FIELD et al., 2014). According to Pham et al. (2019), future coffee priorities should focus on growing regions that are not affected by climate change.

Several studies have related climate change with pests and diseases in agriculture, including *Phakopsora pachyrhizi* and *Spodoptera exigua* in common bean (RAMIREZ-CABRAL, KUMAR, SHABANI, 2019), wheat stem rust (PRANK et al., 2019), coffee rust (ALFONSI et al., 2019), and corn rust (RAMIREZ-CABRAL, KUMAR, SHABANI, 2017). However, few studies have evaluated *C. coffeicola* under climate change scenarios, focusing mainly on Brazil.

Therefore, this study aimed to elaborate an agroclimatic zoning for the incidence of brown eye spot on coffee under climate change scenarios in the main coffee-growing regions of Brazil.

Material And Methods

The study was carried out in traditional areas of coffee cultivation, as well as those with fitness for coffee cultivation, corresponding to the states of Paraná (PR), São Paulo (SP), Rio de Janeiro (RJ), Espírito Santo (ES), Minas Gerais (MG), Goiás (GO), and Bahia (BA). The predominant climate in the study region comprises the tropical and subtropical climate classes, according to the climate classifications by Holdridge (1967) – tropical premontane moist forest, subtropical premontane moist forest, and tropical basal forest – and Köppen (1936) – Aw, Cfa, Cwa, and Cwb (ALVARES et al., 2013).

Climate data of mean (T_{mean} in °C), maximum (T_{max} in °C), and minimum (T_{min} in °C) air temperature, precipitation (P_{mean} in mm), and mean relative humidity (RH_{mean} in %) were collected daily by the National Aeronautics and Space Administration/Prediction of Worldwide Energy Resources – NASA/POWER platform during the period from 1989 to 2020 for 46 municipalities of the study region (Figure 1). The NASA/POWER platform provides agrometeorological data in cell grid coverage, with a spatial resolution of 1° latitude-longitude (ZHANG et al., 2010; STACKHOUSE, 2015) and a high potential for modeling agricultural crops (MONTEIRO, SENTELHAS, STONE, 2018).

The daily maximum (RH_{max}) and minimum (RH_{min}) relative humidity values were estimated following FAO-56 Crop evapotranspiration – Guidelines for computing crop water requirements (Allen et al., 1998), using the dew point temperature (T_{dew}) associated with estimated saturation vapor pressure data at

maximum ($es_{T_{max}}$) and minimum ($es_{T_{min}}$) air temperatures. Qiu et al. (2021) also used this method. The dew point temperature was estimated through the saturation vapor pressure at mean temperature ($es_{T_{mean}}$) and actual vapor pressure ($ea_{T_{mean}}$), derived from mean relative humidity (RH_{mean}) and mean air temperature, as adopted by Paredes et al. (2018). The data of daily mean relative humidity and daily mean (T_{mean}), maximum (T_{max}), and minimum air temperature (T_{min}) allowed calculating the daily leaf wetness duration (Figure 2).

The hourly air temperature ($T_{air_{hr}}$) values were estimated as established by Campbell (1985), in which the temperature variation is driven by solar irradiance, providing a smooth transition from the daily minimum air temperature to the daily maximum air temperature (BREGAGLIO et al., 2010; BUDDHADEB et al., 2021). RH_{max} , RH_{min} , T_{max} , and T_{min} were used as input data to estimate the relative humidity for each hour of the day (RH_{hr}), using the equation proposed by Waichler and Wigmosta (2003).

The leaf wetness duration (LWD) was calculated using the method proposed by Monteith (1957), in which the number of hours with relative humidity $\geq 90\%$ corresponds to the number of hours of leaf wetness (Figure 2). Beruski et al. (2019) highlighted the accuracy and precision of this model in determining leaf wetness duration, being indicated for entry into the Asian rust alert system in traditional regions for soybean cultivation in Brazil.

The development of *C. coffeicola* was determined using the agrometeorological variables T_{mean} , RH_{mean} , and LWD, designed to correspond to the favorable range of pathogen development (Table 1). The developmental classes of brown eye spot were determined by combining the necessary variables, as follows: high for T_{mean} , RH_{mean} , and LWD in the appropriate range, medium for T_{mean} , RH_{mean} , or LWD out of the appropriate range, and low for the set of two or more variables, limiting the pathogen development.

Table 1. Optimal climate characteristics and incidence of *Cercospora coffeicola*. Source: Synthesis of several authors.

Characteristic	Value
Mean air temperature	18–30 °C ^(1,2)
Relative humidity	> 90% ⁽³⁾
LWD	> 9 hours ^(4,5)

⁽¹⁾ Souza, Maffia and Mizubuti (2012); ⁽²⁾ Vale et al. (2019); ⁽³⁾ Souza et al. (2011); ⁽⁴⁾ Santos et al. (2008); ⁽⁵⁾ De Carvalho Alves et al. (2009).

Climate change scenarios were devised based on sets of climate simulations for the 21st century, varying the mean relative humidity –30% and +30% and increasing the mean air temperature by 1.5 °C and 3 °C, as applied by Pirttioja et al. (2015), to simulate future projections of the fifth report issued by IPCC (IPCC-

AR5) (PACHAURI et al., 2014). The current scenario (S1) corresponds to the current data, with an increase of 0 °C in the mean temperature and +0% in the relative humidity. Scenarios S2 and S3 correspond to an increase of 1.5 °C and 3.0 °C in the mean temperature, respectively, but keeping the relative humidity unchanged. Moreover, scenarios S4 and S5 had a -30% reduction and a +30% increase for relative humidity, respectively, but keeping the mean temperature unchanged, identical to the current scenario.

Spatial interpolation was performed for all climate elements at all locations using a geographic information system (GIS) by the kriging method (KRIGE, 1951), with the spherical model, one neighbor, and a spatial resolution of 0.25°. The delimitation for developmental classes of brown eye spot was obtained by superimposing maps of meteorological elements. All the steps for designing the project are shown in Figure 3.

Results And Discussion

The state of Goiás presented the highest mean annual precipitation, with 1700 (± 115) mm, 300 mm more than that recorded by Pena et al. (2016), and the state of Bahia recorded 995 (± 27) mm per year, the lowest values recorded among the other states. Paraná, São Paulo, Espírito Santo, Minas Gerais, Rio de Janeiro, and the Federal District presented means of 1588 (± 36) mm, 1388 (± 73) mm, 1242 (± 57) mm, 1388 (± 91) mm, 1351 (± 66) mm, and 1532 (± 106) mm, respectively (Figure 4). These results are in accordance with Alvarez (2013).

May to September is the period with the lowest water supply among the Arabian coffee-producing regions. Monthly precipitation of less than 50 mm is observed between the regions of Minas Gerais, Goiás, DF, and northern and western Bahia from May to August. Eastern Bahia presents values above 50 mm in the period of lowest precipitation, as observed for the state of Paraná (Figure 5). Aparecido et al. (2019) found a variation from 476.6 to 638.1 mm in the summer for the state of Paraná.

December has the highest precipitation rates in the entire study region, with means between 200 and 250 mm in northern Paraná, São Paulo, Rio de Janeiro, southern Minas Gerais, and Goiás. Few locations have precipitation higher than 250 mm, such as western Goiás and extreme southern Minas Gerais. According to Rebiota (2015), the state of Minas Gerais can reach precipitation of 900 mm in the central-south in the summer.

The mean annual temperature showed higher values for the states of Bahia and Goiás, with values of 23.61 (± 1.39) °C and 22.96 (± 1.58) °C, respectively. Espírito Santo, Paraná, São Paulo, Rio de Janeiro, Minas Gerais, and the Federal District showed annual means of 21.52 (± 2.14) °C, 19.80 (± 2.80) °C, 20.63 (± 2.36) °C, 20.96 (± 2.39) °C, 20.08 (± 2.04) °C, and 20.98 (± 1.51) °C, respectively (Figure 6). These values were corroborated by Casaroli et al. (2018).

May to August is the period that shows a reduction in the mean temperature (Figure 7), with values lower than 15°C observed in southern Paraná. Southern Minas Gerais and western São Paulo have a mean

temperature between 18 and 21°C. Aparecido et al. (2019) observed thermal and water variations in the Southeast from 16.5 to 22.6°C and 800 to 2,800 mm, respectively.

February has the highest mean temperature in the region, with a value between 24 and 27°C, observed in Rio de Janeiro, Bahia, Espírito Santo, western Goiás, and the north of the states of Paraná, São Paulo, and Minas Gerais. Indices above 27°C were recorded only in northern Bahia. Medauar et al. (2020) also found a mean air temperature of 25.3°C in February for the state of Bahia.

All regions presented higher relative humidity between November and May, with indices above 60%, except for the extreme northern Minas Gerais and northern Bahia, which presented values below 60% (Figure 8). March presented relative humidity above 80% in the Federal District, Espírito Santo, western São Paulo and Paraná, and the entire southern region of Minas Gerais.

The period of lowest relative humidity is between June and October, with values below 40% in western Bahia and northern Goiás for July, August, and September. However, the humidity remained high along the entire coastline, with 70 and 80% due to moisture coming from the sea. Few locations had indices above 80%, as observed in São Paulo, Minas Gerais, Paraná, and Bahia. These results corroborate with Alvarez et al. (2015).

Leaf wetness duration showed seasonality similar to the distribution of relative humidity and precipitation (Figure 9). The longest leaf wetness durations were recorded from November to June, with indices above 6 hours in most of the evaluated states, as observed by Alvares et al. (2015). Regions characterized by high relative humidity (Figure 8), high precipitation volumes (Figure 5), and milder temperatures (Figure 7) correspond to locations with a longer leaf wetness duration. Paraná had the longest leaf wetness durations, reaching values above 12 hours in the extreme south of the state for June and July. On the other hand, northern Bahia presents values lower than 4 hours, mainly from May to December. Urashima et al. (2018) reported a variation between the area of orange rust lesions on sugarcane with the leaf wetness duration.

The current scenario presented two climate risk classes (medium and low) for the occurrence of brown eye spot on coffee (Figure 10). Low risk for brown eye spot was observed in all months of the year, except for eastern Bahia from May to June. Areas close to the coastline showed a medium risk only from April to August in up to 19.98% of the state of Bahia (Figure 11A). Bigirimana et al. (2012) found a reduction in the incidence of coffee rust at high altitudes.

The north, northeast, and northwest of Minas Gerais, one of the main coffee-producing regions in Brazil, have a low risk of brown eye spot throughout the year. However, much of the west, south, and east of the state has a medium risk of the disease between December and April. Paraná, São Paulo, Goiás, and DF presented the most critical periods between January and April, with a medium risk predominating in most states. Moreover, western Espírito Santo presented higher mean risks of brown eye spot. Tunwari and Nahunnaro (2016) observed a variation in the incidence of *Cercospora* sp. in sesame-producing regions

in Nigeria, with the interactions between climate, cultivar, and the different techniques attributed to crop management adopted by local producers.

The Federal District showed a predominance from 91.7–100% of the medium-risk class for the period between December and April (Figure 11B), while this class has a predominance lower than 50% in Espírito Santo, reaching 0% between August and October (Figure 11C). The state of Goiás presented 100% of the territory covered by the low-risk class between June and November (Figure 11D). Minas Gerais presented a predominance above 50% for low climate risk of brown eye spot, reaching 100% in September, but March presented a 56.9% predominance of the medium-risk class (Figure 9E).

Paraná registered the highest intensity of medium risk of brown eye spot in April in 76.2% of the state and a low risk of 92.2% and 95.3% in July and August, respectively (Figure 11F). The period from August to October in Rio de Janeiro represented a low-risk potential for the occurrence of brown eye spot in 100% of the state, while the period from December to June presented a medium intensity in 50% of the state, reaching 75.18% in March (Figure 11G). The state of São Paulo, on the other hand, presented a low risk for the occurrence of brown eye spot from June to December, exceeding 70% of the territory (Figure 11H).

The scenario with an increase of +1.5°C in the mean temperature (S2) presented significant variations relative to the current scenario, with a reduction in areas with medium risk of the disease (Figure 12). Bahia had a predominance of 0.03% for the medium risk zone in June (Figure 13A). Espírito Santo also showed lower indices for the same class, with 2.62%, 2.26%, and 3.17% predominance in March, April, and December, respectively (Figure 13C). The states of Bahia, Federal District, Espírito Santo, Goiás, Minas Gerais, and Rio de Janeiro showed 100% prevalence for the low-risk zone of brown eye spot development between June and November. Changes in temperature patterns in the dynamics of the relationship between environment, pathogen, and host plant can directly influence the number of cycles and the geographic distribution of pathogens during crop development (ANGELOCCI, GHINI, BETTIOL, 2017).

Paraná (Figure 13F) and São Paulo (Figure 13H) presented, on average, reductions of -36.58% and -45.30% relative to the current scenario, respectively, corresponding to a predominance of less than 50% of the states for the low risk of brown eye spot development from January to April. Moraes et al. (2012) used future scenarios developed by IPCC and also found a reduction in climate favorability for the occurrence of phoma leaf spot on coffee in Brazil.

Scenario S3, which has an increase in the mean temperature of +3.0°C (Figure 14), showed a reduction for the low climate risk zone in the state of Paraná relative to the current scenario, with values of -31.22%, -38.88%, -15.64%, -17.03%, and -15.21% from May to September, respectively (Figure 15F). Goiás presented a reduction in the medium climate risk from December to May, with a predominance of 0.06%, 34.35%, 37.98%, 37.98%, 23.05%, and 0.02%, respectively (Figure 15D), representing, on average, a reduction of -70.92% for the same period compared to the current scenario.

The variability of the mean temperature explored in scenarios S2 (Figure 12) and S3 (Figure 14) showed a significant reduction in the medium risk for the occurrence of brown eye spot on coffee in the entire study region, with higher sensitivity in São Paulo, Minas Gerais, Rio de Janeiro, and mainly in Paraná, which was more susceptible to alterations due to the low mean temperature. Silva et al. (2018) reported a reduction in the area under the disease progress curve when evaluating *Cercospora* leaf spot on *Toona ciliata* with increased mean temperature, with higher results with indices between 23 and 24°C associated with increased leaf wetness duration.

The scenario of -30% reduction in relative humidity (S4) showed a predominance of the low-risk class for brown eye spot development on coffee in 100% of the study region during the 12 months evaluated (Figures 16 and 17). It is due to the direct proportionality between relative humidity and leaf wetness duration. Thus, the reduction in relative humidity promoted changes in the climate risk classes for brown eye spot on coffee. As in scenario S1, scenarios S2, S3, and S4 do not present relative humidity above 90%, a determining factor for the development of fungi of the genus *Cercospora* (CARVALHO et al., 2005; LOPES et al., 2012; BUBLITZ et al., 2019; KUMAR et al., 2020). Kumar et al. (2011) observed the germination of *Cercospora canescens* conidia in mung beans with relative humidity above 92%.

Scenario S5, with an increase of +30% in relative humidity, showed higher variability, with the three climate risk classes for the brown eye spot occurrence in all months of the year (Figure 18). High relative humidity represents a key climate attribute for the expansion of climate risk zones for coffee brown eye spot. Nega et al. (2016) found higher severity of the fungus *Cercospora zea-maydis* in regions of intermediate annual humidity and precipitation. A reduction in areas classified as low risk for brown eye spot was observed from November to April, being restricted to areas with low risk only northern Bahia and extreme northern Minas Gerais in April. The period from July to October has a higher predominance of the low-risk class, except for locations close to the coastline, which are predominantly at high risk for brown eye spot development (Figure 18). The state of Goiás and the Federal District presented 100% of the territory with a low risk for brown eye spot in August and September (Figure 19D).

Regarding the high climate risk to the development of brown eye spot, the states of Goiás, São Paulo, Rio de Janeiro, Espírito Santo, and the Federal District showed 100% prevalence from December to April. These periods present a great risk for coffee cultivation, requiring preventive measures such as resistant cultivars and implementation of biological control (HADDAD et al., 2009; SOUZA et al., 2011).

The state of Bahia showed predominance in locations close to the coastline and west, with values below 40% in the evaluated months (Figure 19A). The Federal District presented well-defined periods, with 100% high risk of brown eye spot from November to May, 100% of medium risk from August to October, and 5.66% of low risk from June and July, a period with lower precipitation indices (Figure 19B).

Only Espírito Santo and Paraná did not show the low-risk class in the S5 scenario. The medium-risk class in Paraná represents 4.18%, 66.54%, 98.04%, 98.04%, 86.71%, 69.4%, 14.93%, 12.23%, and 1.89% in the period from April to December, respectively (Figure 19F). Espírito Santo showed a predominance of 2.91%, 2.91%, 27.56%, 55.45%, and 49.8% for the medium-risk class from June to October (Figure 19C).

Goiás had 25.38%, 15.46%, 15.46%, 15.79%, and 5.74% of the state area with a predominance by the medium class of climate risk to brown eye spot in May, June, July, October, and November, respectively (Figure 19D). In the state of Minas Gerais, the highest percentage of area covered by a high risk of brown eye spot was observed in the period from November to May, with 76%, 100%, 97.83%, 89.3%, 93.46%, 80.64%, and 57.77% of the territory, respectively (Figure 19E).

The medium-risk class occurred only from May to October in Rio de Janeiro, reaching 4.51%, 22.36%, 22.36%, 25.04%, 39.08%, and 18.63% of the territory, respectively (Figure 19G). The low-risk class in São Paulo corresponded to 86.17%, 86.17%, 54.62%, 52.9%, and 51.47% of the state in June, July, August, and November, respectively (Figure 19H).

The annual mean of the data for the development potential of brown eye spot on coffee showed that all states had higher development of the low fitness class for scenarios S1, S2, S3, and S4 (Table 1), standing out Bahia, with 94.69% and 99.99% in scenarios S1 and S2, respectively. All the analyzed states present a higher fitness for the development of the high-risk class in Scenario S5, which has a higher increase in relative humidity, standing out Rio de Janeiro and Espírito Santo, with 88.8% and 88.45%, respectively.

Table 1
Percentage of fitness classes for brown eye spot development
on coffee.

State	Class	S1	S2	S3	S4	S5
BA	High	-	-	-	-	30.61
BA	Medium	5.31	0.01	-	-	36.01
BA	Low	94.69	99.99	100	100	33.38
DF	High	-	-	-	-	58.33
DF	Medium	40.97	15.03	7.67	-	0.94
DF	Low	59.03	84.97	92.33	100	40.72
ES	High	-	-	-	-	88.45
ES	Medium	17.55	0.67	0.39	-	11.55
ES	Low	82.45	99.33	99.61	100	-
GO	High	-	-	-	-	55.74
GO	Medium	29.52	14.86	11.12	-	6.49
GO	Low	70.48	85.14	88.88	100	37.77
MG	High	-	-	-	-	51.15
MG	Medium	22.11	11.92	10.51	-	22.83
MG	Low	77.89	88.08	89.49	100	26.02
PR	High	-	-	-	-	62.34
PR	Medium	42.22	28.52	36.1	-	37.66
PR	Low	57.78	71.48	63.4	100	-
RJ	High	-	-	-	-	88.8
RJ	Medium	44.92	11.08	9.22	-	11
RJ	Low	55.08	88.92	90.78	100	0.2
SP	High	-	-	-	-	58.4
SP	Medium	34.98	16.07	16.24	-	32.5
SP	Low	65.02	83.93	83.76	100	9.1

Conclusions

The current scenario presents low and medium climate risk classes for brown eye spot on coffee, with the medium class being more intensified from December to April. The southern region of Minas Gerais shows medium risk between December and May.

The scenarios with an increase in the mean temperature (S2 and S3) showed significant changes in the states of São Paulo, Minas Gerais, Rio de Janeiro, and Paraná, the latter being considered the most susceptible to changes due to low mean temperatures.

The reduction in relative humidity by -30% in scenario S4 showed the development of the low-risk class for all states in all the evaluated months. On the other hand, the increase in relative humidity by +30% in scenario S5 provided the development of all the three climate risk classes for brown eye spot on coffee (low, medium, and high).

Declarations

Conflict of Interest: The authors declare that they have no conflict of interest.

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Code availability: The software used was python and scripts are available

Ethics approval: It is not necessary

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Consent for publication: All authors approved

Authors' contributions:

Rafael F. Lima: Formal analysis, Conceptualization, Methodology, Investigation; Lucas E. O. Aparecido: Project administration, Term, Conceptualization, Methodology, Investigation, Writing - Original draft, Writing – Review & Editing; Guilherme Botega Torsoni: Term, Funding acquisition, Conceptualization, Writing - Review & Editing; Alisson G. Chiquitto: Data Curation, Original draft, Writing - Review & Editing; José R. Moraes: Writing - Review & Editing; Glauco S. Rolim: Visualization, 308 Writing Original draft, Writing - Review & Editing.

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Figures

Figure 1

Location of the largest coffee-producing region in Brazil.

Figure 2

Flowchart showing the calculation of the leaf wetness duration (LWD), where $e_{sT_{mean}}$ is the saturation vapor pressure (kPa) at mean air temperature ($^{\circ}\text{C}$), T_{mean} is the mean air temperature ($^{\circ}\text{C}$), $e_{aT_{mean}}$ is the current vapor pressure (kPa) derived from relative humidity and mean air temperature, RH_{mean} is the

mean relative humidity (%), T_{dew} is the dew point temperature ($^{\circ}\text{C}$) derived from relative humidity, $e_{s_{T_{\text{dew}}}}$ is the saturation vapor pressure (kPa) at dew point temperature, $e_{s_{T_{\text{min}}}}$ is the saturation vapor pressure (kPa) at minimum air temperature, T_{min} is the minimum air temperature ($^{\circ}\text{C}$), $e_{s_{T_{\text{max}}}}$ is the saturation vapor pressure (kPa) at maximum air temperature, T_{max} is the maximum air temperature ($^{\circ}\text{C}$), RH_{max} is the maximum relative humidity (%), RH_{min} is the minimum relative humidity (%), $T_{\text{air_hr}}$ is the hourly air temperature ($^{\circ}\text{C}$), h is the time of day, TimeVar is the time of the day corresponding to the maximum air temperature record, and RH_{hr} is the hourly relative humidity (%).

Figure 3

Flowchart of the used methodology.

Figure 4

Boxplot of annual precipitation distribution for each coffee-producing state in Brazil.

Figure 5

Spatial representation of the mean monthly precipitation for Arabian coffee-producing regions in Brazil.

Figure 6

Boxplot of the mean annual air temperature distribution for each coffee-producing state in Brazil.

Figure 7

Spatial representation of the mean monthly air temperature for Arabian coffee-producing regions in Brazil.

Figure 8

Spatial representation of the mean monthly relative humidity for Arabian coffee-producing regions in Brazil.

Figure 9

Spatial representation of the mean monthly leaf wetness duration for Arabian coffee-producing regions in Brazil.

Figure 10

Spatial representation of the brown eye spot risk zoning for coffee-producing regions in the current scenario (S1).

Figure 11

Percentage of areas with low or medium climate risk for brown eye spot in each state according to the months of the year in the current scenario. S1 = Current scenario, BA = Bahia, DF = Federal District, ES = Espírito Santo, GO = Goiás, MG = Minas Gerais, PR = Paraná, RJ = Rio de Janeiro, SP = São Paulo.

Figure 12

Spatial representation of the brown eye spot risk zoning for coffee-producing regions under the scenario with an increase of +1.5 °C (S2).

Figure 13

Percentage of areas with low or medium climate risk for brown eye spot in each state according to the months of the year in the S2 scenario. S2 = Scenario with +1.5 °C increase in the mean temperature, BA = Bahia, DF = Federal District, ES = Espírito Santo, GO = Goiás, MG = Minas Gerais, PR = Paraná, RJ = Rio de Janeiro, SP = São Paulo.

Figure 14

Spatial representation of the brown eye spot risk zoning for coffee-producing regions under the scenario with an increase of +3.0 °C (S3).

Figure 15

Percentage of areas with low or medium climate risk for brown eye spot in each state according to the months of the year in the S3 scenario. S3 = Scenario with +3 °C increase in the mean temperature, BA = Bahia, DF = Federal District, ES = Espírito Santo, GO = Goiás, MG = Minas Gerais, PR = Paraná, RJ = Rio de Janeiro, SP = São Paul.

Figure 16

Spatial representation of the brown eye spot risk zoning for coffee-producing regions under the scenario with -30% relative humidity (S4).

Figure 17

Percentage of areas with low or medium climate risk for brown eye spot in each state according to the months of the year in the S4 scenario. S4 = Scenario with -30% decrease in relative humidity, BA = Bahia, DF = Federal District, ES = Espírito Santo, GO = Goiás, MG = Minas Gerais, PR = Paraná, RJ = Rio de Janeiro, SP = São Paulo.

Figure 18

Spatial representation of the brown eye spot risk zoning for coffee-producing regions in the scenario with 30% relative humidity (S5).

Figure 19

Percentage of areas with low, medium, or high climate risk for brown eye spot in each state according to the months of the year in the S5 scenario. S4. S4 = Scenario with +30% increase in relative humidity, BA = Bahia, DF = Federal District, ES = Espírito Santo, GO = Goiás, MG = Minas Gerais, PR = Paraná, RJ = Rio de Janeiro, SP = São Paulo.