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Article

Climate Change and *Phoma* spp. Leaf Spot of Arabica Coffee: A CMIP6 Modeling Approach

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Abstract

Coffee is currently one of the main commodities traded in the world. Brazil is the largest producer and exporter of the grain. Fungal diseases are very common in coffee crops and control represents a large part of coffee production costs. The climate is an essential factor in the development of a disease such as phoma leaf spot. This disease is favored by high atmospheric humidity and mild temperatures. In this context, this study aimed to carry out the climatic favorability zoning for one of the main coffee diseases (*Phoma ssp.*) of the coffee-growing region in Brazil. The study was conducted in the main traditional coffee growing regions, i.e., the states of Paraná (PR), São Paulo (SP), Rio de Janeiro (RJ), Espírito Santo (ES), Minas Gerais (MG), Goiás (GO), and Bahia (BA), totaling 2730 municipalities. Air temperature and daily precipitation data for the current scenario were collected from the WorldClim version 2.1 platform for the latest climatological normal in GeoTIFF format. Future climate variables were obtained by the WorldClim 2.1 platform for the IPSL-CM6A-LR global climate model for the periods 2021-2040, 2041-2060, 2061-2080, and 2081-2100 and the scenarios SSP-1 2.6, SSP-2 4.5, SSP-3 7.0, and SSP-5 8.5, respectively. Thus, zoning was carried out using software of geographic information systems (QGIS), automated with the Python language. Also, graphs were prepared to better represent the results. About 54.77% of the coffee-producing region presented relatively favorable conditions for the development of Phoma leaf spot, 30.55% favorable, 3.20% highly, and 11.48% showed no climate conditions for the occurrence of the disease. The climate conditions from October to March favored the occurrence of phoma leaf spot. The *Phoma spp.* Leaf spot will probably reduce its occurrence in all future scenarios due to the loss of favorable climate conditions. During the period 2081-2100, 85.03% of the entire region would be unfavorable to the development of homas pp. For the most pessimistic scenario (SSP-5 8.5). Climate changes will provide unsuitable conditions for the development of *Phoma spp*.

Keywords: agricultural adaptation, coffee planting, disease prediction, climate variability, IPCC.

Mudanças Climáticas e a Mancha Foliar de *Phoma spp.* no Café Arábica: Uma Abordagem de Modelação CMIP6

Resumo

O café é atualmente uma das principais commodities negociadas no mundo. O Brasil é o maior produtor e exportador do grão. Doenças fúngicas são muito comuns nas lavouras de café, e o controle representa uma grande parte dos custos de produção do café. O clima é um fator essencial no desenvolvimento de uma doença, como a mancha de folha de phoma. Essa doença é favorecida pela alta umidade atmosférica e temperaturas amenas. Nesse contexto, este estudo teve como objetivo realizar o zoneamento da favorabilidade climática para uma das principais doenças do café (*Phoma ssp.*) na

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região cafeeira do Brasil. O estudo foi conduzido nas principais regiões tradicionais de cultivo de café, ou seja, nos estados do Paraná (PR), São Paulo (SP), Rio de Janeiro (RJ), Espírito Santo (ES), Minas Gerais (MG), Goiás (GO) e Bahia (BA), totalizando 2730 municípios. Dados de temperatura do ar e precipitação diária para o cenário atual foram coletados da plataforma WorldClim versão 2.1 para a última normal climatológica no formato GeoTIFF. Variáveis climáticas futuras foram obtidas pela plataforma WorldClim 2.1 para o modelo climático global IPSL-CM6A-LR para os períodos 2021-2040, 2041-2060, 2061-2080 e 2081-2100, e os cenários SSP-1 2.6, SSP-2 4.5, SSP-3 7.0 e SSP-5 8.5, respectivamente. Assim, o zoneamento foi realizado usando software de sistemas de informação geográfica (QGIS), automatizado com a linguagem Python. Além disso, gráficos foram preparados para melhor representar os resultados. Cerca de 54,77% da região produtora de café apresentou condições relativamente favoráveis para o desenvolvimento da mancha de folha de Phoma, 30,55% favorável, 3,20% altamente e 11,48% não apresentou condições climáticas para a ocorrência da doença. As condições climáticas de outubro a março favoreceram a ocorrência da mancha de folha de phoma. A mancha de folha de *Phoma spp.* provavelmente reduzirá sua ocorrência em todos os cenários futuros devido à perda de condições climáticas favoráveis. Durante o período 2081-2100, 85,03% de toda a região seria desfavorável ao desenvolvimento de *Phoma spp*. para o cenário mais pessimista (SSP-5 8.5). As mudanças climáticas proporcionarão condições inadequadas para o desenvolvimento de *Phoma spp*.

Palavras-chave: adaptação agrícola, plantio de café, previsão de doenças, variabilidade climática, IPCC.

1. Introduction

Coffee is currently one of the main commodities traded around the world (Clarke and Vitzthum, 2001), with huge participation in the world economy (Vegro and Almeida, 2020). Brazil is the world's largest producer of the crop (Volsi *et al*., 2019), representing 30% of world production (ICO, 2022, p. 4). It represents a production of a mean of 69 million bags, about 30% of world coffee production (CONAB, 2022; ICO, 2022). The Southeast region of Brazil concentrates most of the national production, and Minas Gerais is the largest producer, followed by Espírito Santo, São Paulo, Bahia, and Paraná, representing approximately 90% of the total production in Brazil (CONAB, 2022).

Coffea arabica is a perennial crop with a cycle of approximately 24 months, starting with floral initiation and ending with fruit ripening (Camargo and Camargo, 2001). Coffee develops its reproductive structures, such as the pinhead stage (initial structure of fruits) and filling of grains, in the second phenological year (Rakocevic *et al*., 2020), consisting of periods of high susceptibility of the crop to diseases, which may lead to great reductions in productivity (Melke and Fetene, 2014). The disease is one of the main factors that cause economic losses in coffee production (Cerda *et al*., 2017). *Phoma* sp. Is among the main diseases that attack coffee and has been causing significant damage to coffee crops (Moraes *et al*., 2012).

Phoma ssp. Is a very broad fungus genus with more than 2000 species, grouped into nine sections (Aveskamp *et al*., 2008). Among them, approximately 110 species are pathogenic (Deb *et al*., 2020). Some species are related to significant damage in the *Coffea arabica* crop, mainly in its shoots (Mohammed and Jambo, 2015). Some species have already been identified in Brazil, the most common being *Phoma* sp., with great power of penetration and the form of infecting the host (Salgado and Pfenning, 2000). In general, the fungus attacks the leaves, flowers, fruits, and branches of coffee trees, regardless of the species (Deb *et al*., 2020). It causes direct damage to the final production since the interruption of physiological processes occurs, such as the death of floral buds, new shoots, fruit drops, and poor fruit filling (Aveskamp *et al*., 2008).

The disease is controlled mainly by fungicides with the active ingredient azoxystrobin (Parra *et al*., 2019), and preventive measures are important to minimize costs, such as choosing well-drained and wind-protected areas. *Phomas pp*. Attacks mainly during the coffee flowering period and is strongly conditioned by climate conditions.

Air temperature between 15 and 20 °C, precipitation above 4 mm daily, and high relative humidity (>80%) (Salgado *et al*., 2003; Zambolim, 1999) greatly favor the disease. Thus, knowing the seasons with the highest disease incidence based on climate conditions is essential for greater success in controlling phoma leaf spot (Strange and Scott, 2005). The control of phoma leaf spot is currently still a major challenge for producers (Segura *et al*., 2004), requiring the adoption of a series of measures aimed mainly at preventing the onset of the disease and facilitating chemical control (Saab *et al*., 2014).

Climate changes are long-term changes in climate patterns (Fritze *et al*., 2008). They can be natural through the variation of the solar cycle or due to the interference of human activities (Wuebbles and Jain, 2001). In the last century, the air temperature has increased by 1 ± 0.2 °C, with projections up to 2100 showing an increase of up to 1.5 to 6 °C (IPCC, 2014, 2018). These changes are mainly related to an increase in the concentration of greenhouse gases, such as nitrous oxide, carbon dioxide, and ozone, leading to an increase in temperature (Wei *et al*., 2016).

The United Nations Intergovernmental Panel on Climate Change (IPCC) was created aiming at a greater understanding of climate change, based on several studies (Smith *et al*., 2009). IPCC develops comprehensive Assessment Reports on the state of scientific, technical, and socio-economic knowledge about climate change, its future impacts and risks, and options for reducing the speed at which climate change has been occurring (Swart *et al*., 2003).

Climate projection models are unique tools to investigate climate characteristics and behavior (Lucarini *et al.*, 2014). Climate models and their components are gradually developed over the years based on several variables such as long-term greenhouse gases, ozone, atmospheric aerosols, or land surface properties (Randall *et al.*, 2007).

The sixth phase of the Coupled Model Intercomparison Project (CMIP6) is an international project to compare the results of climate model simulations performed according to a common IPCC protocol (Lurton *et al.*, 2020). Among the project models, the IPSL-CM6A-L is composed of the LMDZ atmospheric model version 6A-LR (Hourdin *et al.*, 2020), the NEMO ocean model version 3.6, and the ORCHIDEE land surface model version 2.0, showing future climate projection scenarios, that is, the Shared Socioeconomic Pathways (SSPs) (126, 245, 370, and 585) (Aumont *et al.*, 2015).

Crops will certainly be affected by phytosanitary conditions in a future scenario (Ghini *et al*, 2008). The impacts of climate change can be positive or negative and may increase or decrease the severity of some diseases, varying between regions (Luck *et al*., 2011). Thus, it may directly affect the productivity of various crops such as coffee, which is negatively influenced by diseases throughout its cycle (Gautam *et al*., 2013).

Thus, a climatic risk zoning for the possible occurrence of the fungus *Phoma* ssp. Is an essential tool for agricultural planning and the establishment of coffee plantations. Some studies have used this technique to identify regions and periods most conducive to the development of plant diseases based on climate variables. In this context, Monteiro Galvão, *et al*. (2022) carried out a climatic risk zoning for cocoa frosty pod rot disease in Northeast Brazil under the influence of the ENSO phases and identified that the coastal region has the greatest potential for the occurrence of this disease in the state of Bahia.

In this context, the aim of this study was to conduct climate favorability zoning for one of the primary diseases affecting coffee (*Phomas pp*.) in the coffee-growing region of Brazil.

2. Material and Methods

2.1. Study site

The study was conducted in the states of Paraná (PR), São Paulo (SP), Rio de Janeiro (RJ), Espírito Santo (ES), Minas Gerais (MG), Goiás (GO), and Bahia (BA). These states are traditional coffee-growing regions in Brazil, totaling 2,037,026 km^2, 1,369,410 ha cultivated with coffee, which represents 95% of the total areas cultivated with coffee in the country. The predominant climate in the study region comprises the tropical and subtropical climate classes, according to the climate classifications of Holdridge (1967), that is, tropical premontane humid forest, subtropical premontane humid forest, and basal tropical forest, and Köppen (1936), i.e., Aw, Cfa, Cwa, and Cwb (Alvares *et al*., 2013), as seen in Fig. 1.

2.2. Current data acquisition

Air temperature and daily precipitation data for the current scenario were collected using the WorldClim version 2.1 platform (Fick and Hijmans, 2017) for the last climatological normal. The data are available in GeoTIFF format (.tif), with a 30-second resolution (1 km^2).

2.3. Future data acquisition (IPSL-CM6A-LR)

Future climate variables were obtained from the WorldClim 2.1 platform for the IPSL-CM6A-LR model (Boucher, 2020) of the Institute Pierre-Simon Laplace Climate Modeling Centre (IPSL-CMC), in France, with a 30-second resolution (1 km^2). The IPSL-CM6A-LR model consists of three models: the LMDZ atmospheric general circulation model version 6A-L (Hourdin *et al*., 2020); NEMO (Nucleus for European Models of the Ocean) ocean component, which is divided into three models: NEMO-OPA ocean physics component (Madec, 2008), NEMO-LIM3 glacier and ocean dynamics (Rousset *et al*., 2015; Vancoppenolle *et al*., 2009), and the NEMO-PISCES ocean biochemical factor (Aumont *et al*., 2015); and the ORCHIDEE terrestrial surface component version 2.0 (Krinner *et al*., 2005). This model is part of phase six of the IPCC Coupled Model Intercomparison Project (CMIP6), with major contributions to this project (Lurton *et al*., 2020).

2.4. Shared Socioeconomic Pathways

CMIP6 models are more accurate than the previous version (CMIP5) (Luo *et al*., 2022). The model provides data for all scenarios in the sixth IPCC report, SSPs. All Shared Socioeconomic Pathways scenarios available for four periods (2021-2040, 2041-2060, 2061-2081, and 2081-2100) on the WorldClim platform were used: SSP-1 2.6, SSP-2 4.5, SSP-3 7.0, and SSP- 5 8.5 (Riahi *et al*., 2017). Each scenario simulates the concentration of greenhouse gases in the atmosphere, associated with the simulation of socioeconomic measures taken by society. SSP-1 2.6 is considered the most optimistic, as it presents more sustainable measures and a low accumulation of gases in the atmosphere in 2100. Its radiative forcing level reaches 2.6 W m^{-2} by 2100. On the other hand, SSP-5 8.5 is the most pessimistic scenario, as it presents a simulation in which society does not take sustainable measures, thus increasing the concentration of greenhouse gases in the atmosphere (Kriegler *et al*., 2017; Van Vuuren *et al*., 2017), resulting in a radiative forcing of up to 8.5 W m^{-2} by 2100.

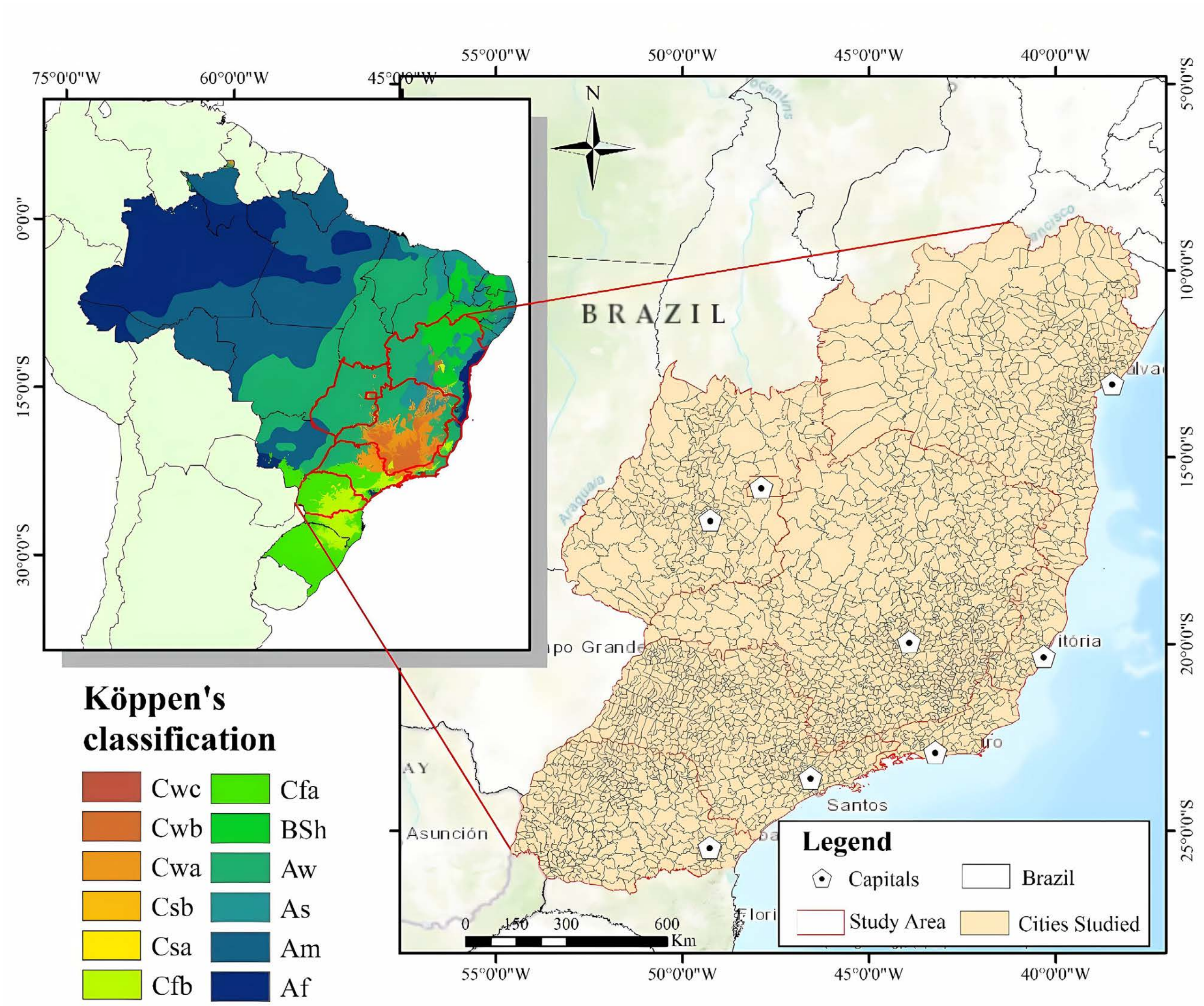

Figure 1 - Location of the areas with the highest coffee production in Brazil.

2.5. Aptitude key

Agrometeorological variables of mean air temperature (T_{mean}) and global solar irradiance (R_{day}), designed to correspond to the favorable range of pathogen development, were used to determine the development of *Phomas pp*. Phoma development classes were determined by combining the necessary variables (Fig. 2).

2.6. Favorability zoning

Figure 3 shows the summary of procedures for carrying out the phoma favorability zoning. First, the raster of air temperature and daily precipitation consisted of inputs. The reclassify tool was applied in the first step (Step 1) to reclassify the images based on the favorability key (Fig. 3). The reclassified images were combined in step 2 by adding a column in the attribute table aiming to add the following aptitude classes: 1 = unfavorable, 2 = relatively favorable, 3 = favorable, and 4 = highly favorable.

The raster combine was converted to a polygon in Step 3 with the new column. In the next step (Step 4), the polygon was dissolved as a function of the column with the favorability classes. Still in Step 4, the intersect tool was applied to add the columns of states and cities from the Shape Region, which had the geographic division of the region, in addition to the total area of each municipality and state. This process aimed to identify the favorability classes in each state and city. Step 5 consisted of the area calculation, for which two columns were activated, one for the polygon area and another for the percentage area. Thus, the area of each polygon was calculated, and the "Area" column was filled in and then the value of this column was divided by the "area_total" of the "Shape Region", obtaining the percentage area of each class within the state or municipality. Finally, the final polygon was exported to a spreadsheet file (Fig. 3).

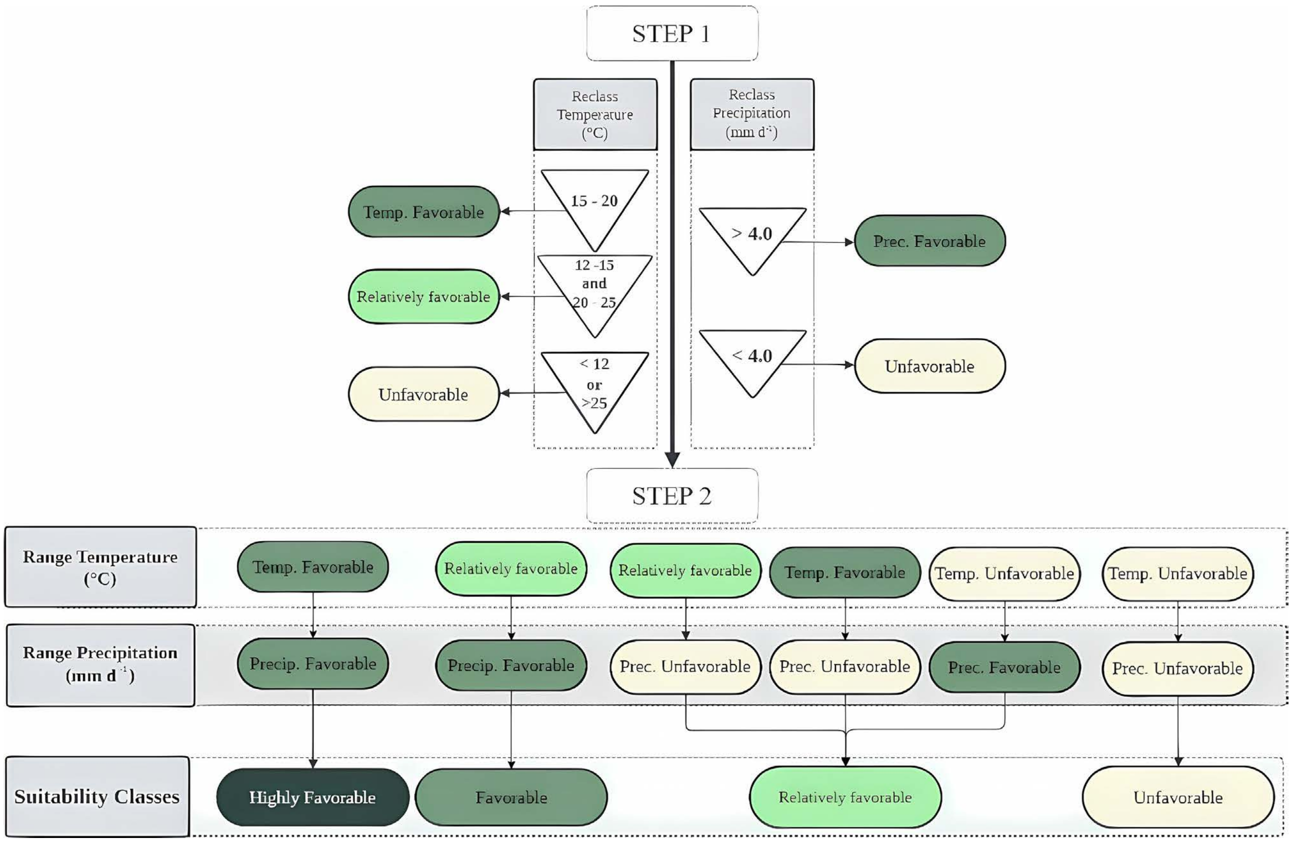

Figure 2 - Optimal climate characteristics for the incidence of *Phomas pp*. Source: Zambolim *et al*. (1999) and Salgado *et al*. (2003).

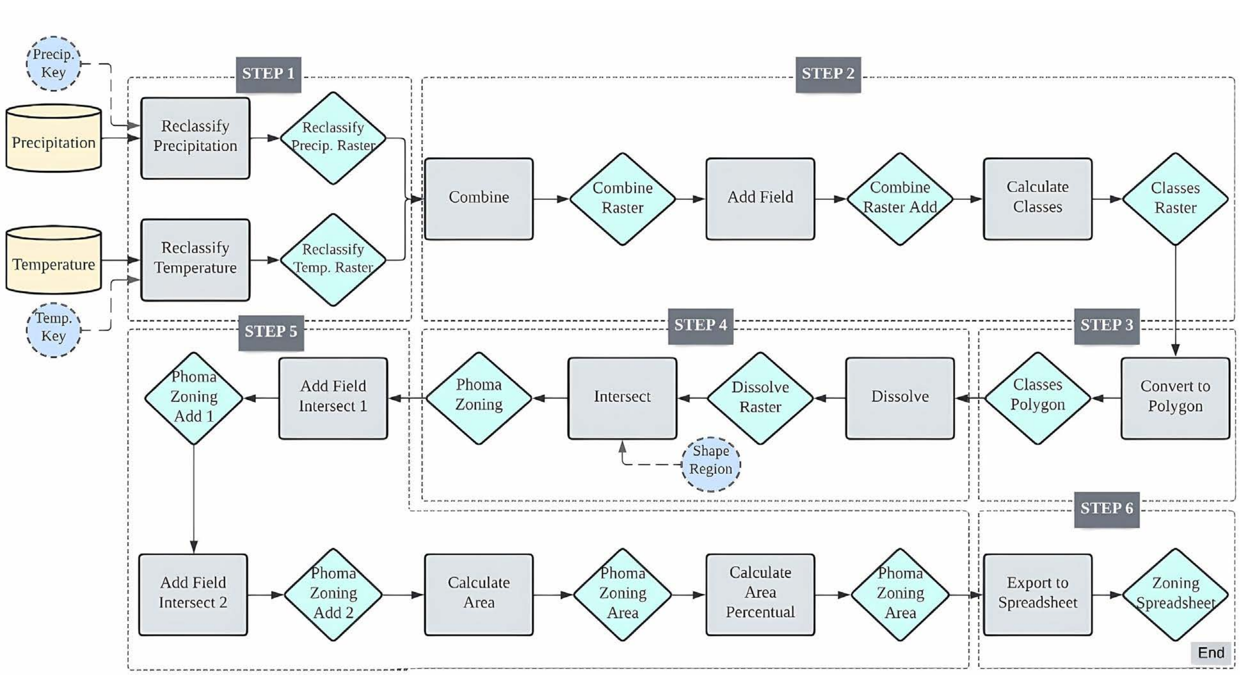

Figure 3 - Flowchart representing the steps for preparing the *Phoma* spp. favorability zoning. Step 1: reclassify; Step 2: combine; Step 3: convert to polygon; Step 4: dissolve and intersect; Step 5: calculate area; Step 6: export to a spreadsheet.

All these steps were condensed into a tool using the QGIS geographic information system software. Choosing the QGIS system for our study offers a variety of benefits. QGIS is an open-source geographic information system that enables users to create, edit, visualize, analyze, and publish geospatial information (Henrico *et al*., 2021). The Python 3.8 programming language was used to automate the elaboration of the favorability zoning of *Phoma* spp. In total, 204 maps were created (4 periods x 4 scenarios x 12 months + 12 current zonings) with a processing time of 34 minutes. The development of all the analyses used in the work followed the steps informed in the flowchart in Fig. 4.

2.7. Additional figures

Box plots were created to visualize the variation in air temperature and daily precipitation as a result of climate change. Charts are tools to provide information clearly (Novick, 2000), and box plots stand out for describing large databases very well (Babura *et al*., 2018).

Circular bar charts were constructed to describe the seasonal variation of favorability zoning in the study region for each period of climate change. Finally, a figure summarizing the variation in the total percentage of the area of each zoning class in each scenario for all periods was elaborated.

3. Results and Discussion

3.1. Current climate

The temporal variation of the climate variables air temperature and rainfall for the studied region showed means of 21.9 ± 1.7 °C and 3.5 ± 1.8 mm day^{-1}, respectively (Fig. 4). The variation in air temperature ranged from 14.6 to 25.0 °C (Fig. 5a). February was the period with the highest mean air temperature (23.7 ± 1.0 °C). In contrast, July showed the lowest mean (18.9 ± 2.0 °C). The mean daily precipitation ranged from 0.2 to 9.1 mm throughout the year (Fig. 5b). December consisted of the period with the highest mean throughout the year, with a value of 6.8 ± 1.3 mm day^{-1}. August was the driest month of the year, with a mean of 0.9 ± 0.5 mm (Fig. 5b).

3.2. Future climate

The climate change scenarios showed great variations compared to the current scenario for the studied region (Fig. 6). It demonstrates the possibility of a sharp increase in temperature in the short term, which could directly affect the behavior of the fungus *Phoma* spp. (Navarro *et al*., 2008). SSP-1 2.6 presented the most optimistic scenario in terms of air temperature in the period 2021-2040, with a mean of 22.8 ± 1.8 °C and an increase of 4.0% relative to the current scenario (Fig. 6a). On the other hand, SSP-5 8.5 in the period 2081-2100 showed the

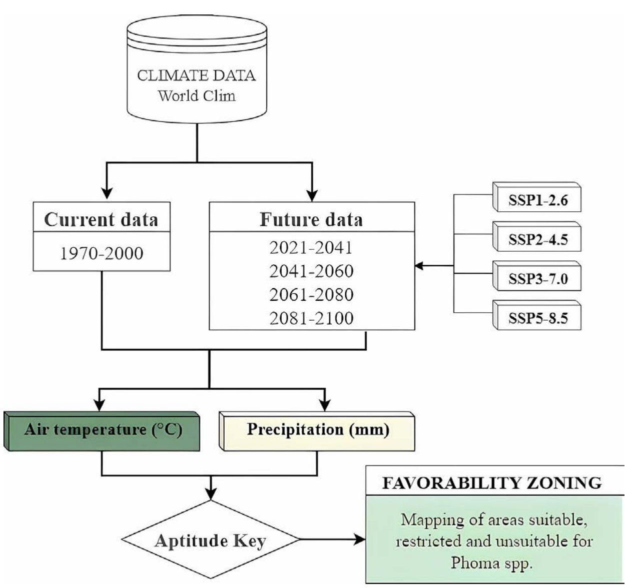

Figure 4 - Flowchart representing the steps taken to obtain the *Phoma spp.* climate classification.

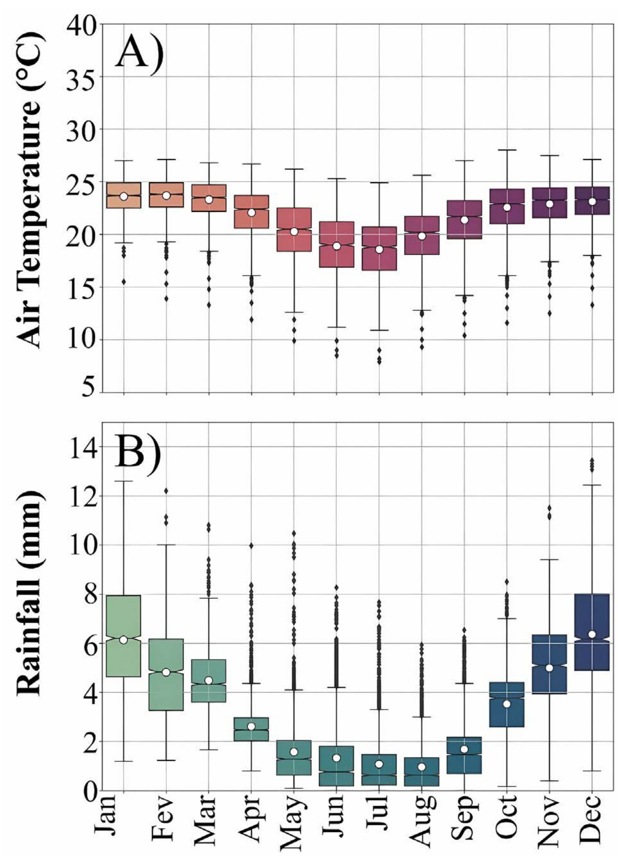

Figure 5 - Box plots showing the seasonal variation of current air temperature (A) and daily precipitation (B) data for all Brazilian coffee-producing states (Bahia, Goiás, Minas Gerais, Espírito Santo, Rio de Janeiro, São Paulo, and Paraná).

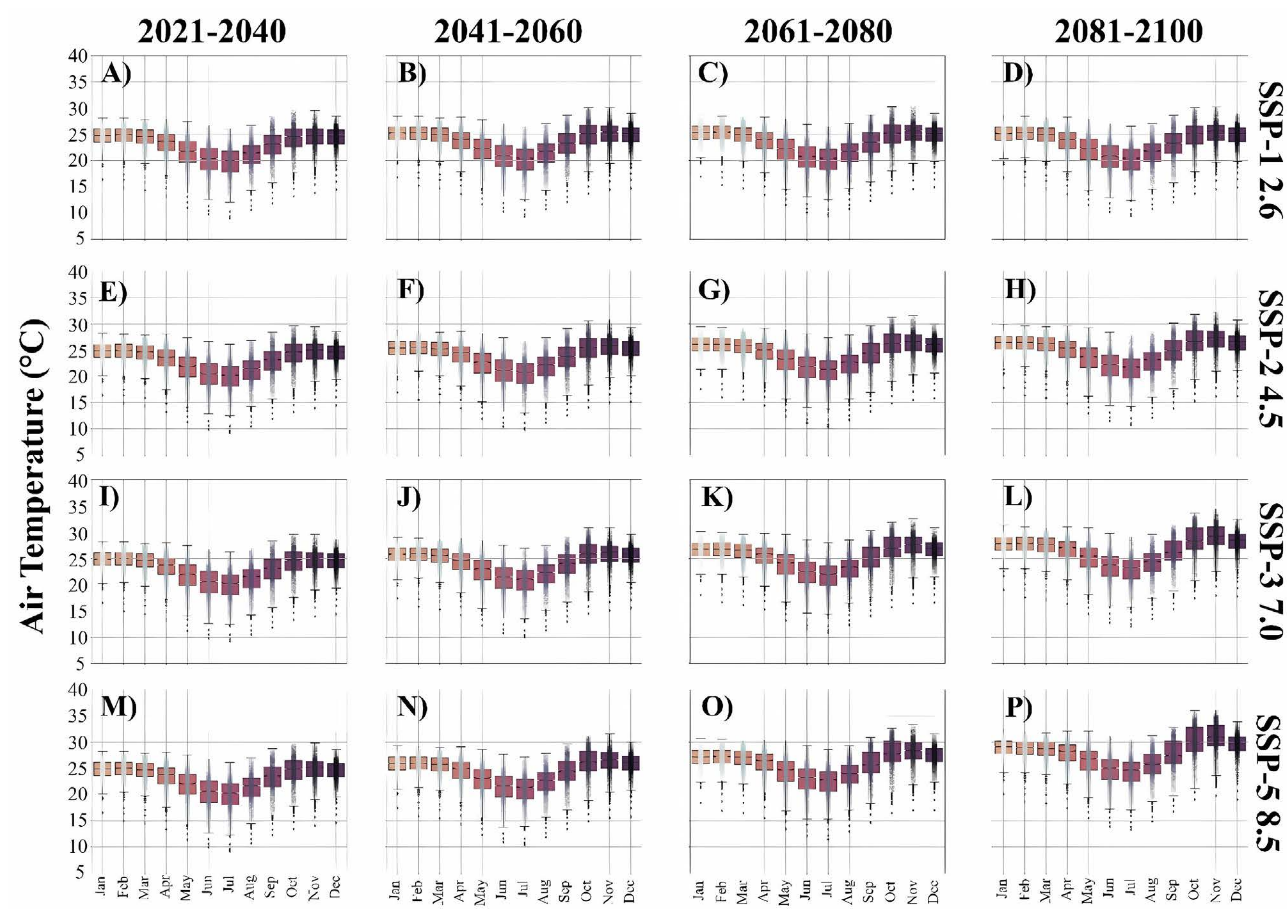

Figure 6 - Box plots representing the seasonal variation of air temperature data in different periods and climate change scenarios.

highest temperature increase among all scenarios compared to the current scenario (28.4%), with a mean of 28.2 ± 2.0 °C (Fig. 6p). These scenarios warn that possible future climate conditions could compromise the development of microorganisms (Compant *et al*., 2010).

The mean daily precipitation in the climate change scenarios showed a reduction compared to the current scenario (Fig. 7). SSP-3 7.0 presented the lowest reduction in precipitation in the period 2021-2040, with an annual mean of 3.4 ± 2.0 mm day^{-1} and a reduction of 1.9% (Fig. 7i). The scenario SSP-5 8.5 showed the highest reduction in the period 2081-2100 (12.5%), with an annual mean of 3.0 ± 1.9 mm day^{-1} (Fig. 7p). January presented the highest daily precipitation in SSP-3 7.0 in the period 2081-2100, with a mean of 7.0 ± 2.0 mm, showing a change relative to the current scenario, whose highest mean was December. August also presented the lowest daily mean precipitation, with 0.8 ± 0.5 mm in the SSP-5 8.5 scenario in 2081-2100 (Fig. 7p).

3.3. Current *Phoma* spp. favorability zoning

Zoning for regions favorable to the development of *Phoma* spp. showed seasonal and spatial variation (Fig. 8). The mean for the unfavorable, relatively favorable, favorable, and highly favorable classes for the region was 11.5, 54.8, 30.5, and 3.2%, respectively. The highest values between October and March occurred for favorable (63.8%) and highly favorable (4.7%) areas. December and January stood out for presenting 74.5 and 68.9% of the region favorable to *Phoma* spp., respectively. Still, October had the largest area classified as highly favorable, i.e., 234,756.54 km^2 (11.6%), requiring higher attention for phoma leaf spot management.

The predominant class between April and September was relatively favorable (Fig. 8). This is the driest period in the region, with lower rainfall rates, which impair spore germination (Dawidziuk *et al*., 2012). In July, 96.6% of the area was classified as relatively favorable and only 2.4% as favorable. September concentrated the largest area classified as unfavorable, but it had 5.2% of the territory as highly favorable.

Minas Gerais, which is the state with the highest Arabica coffee production, had higher favorability to phoma leaf spot. This State has a mean production of 2,064,689 tons (IBGE, 2021) and 82.9% of its territory was favorable to *Phoma* spp. from November to March. In December, 94.3% of the State's territory was favorable. The formation of flower buds or filling of grains occur in

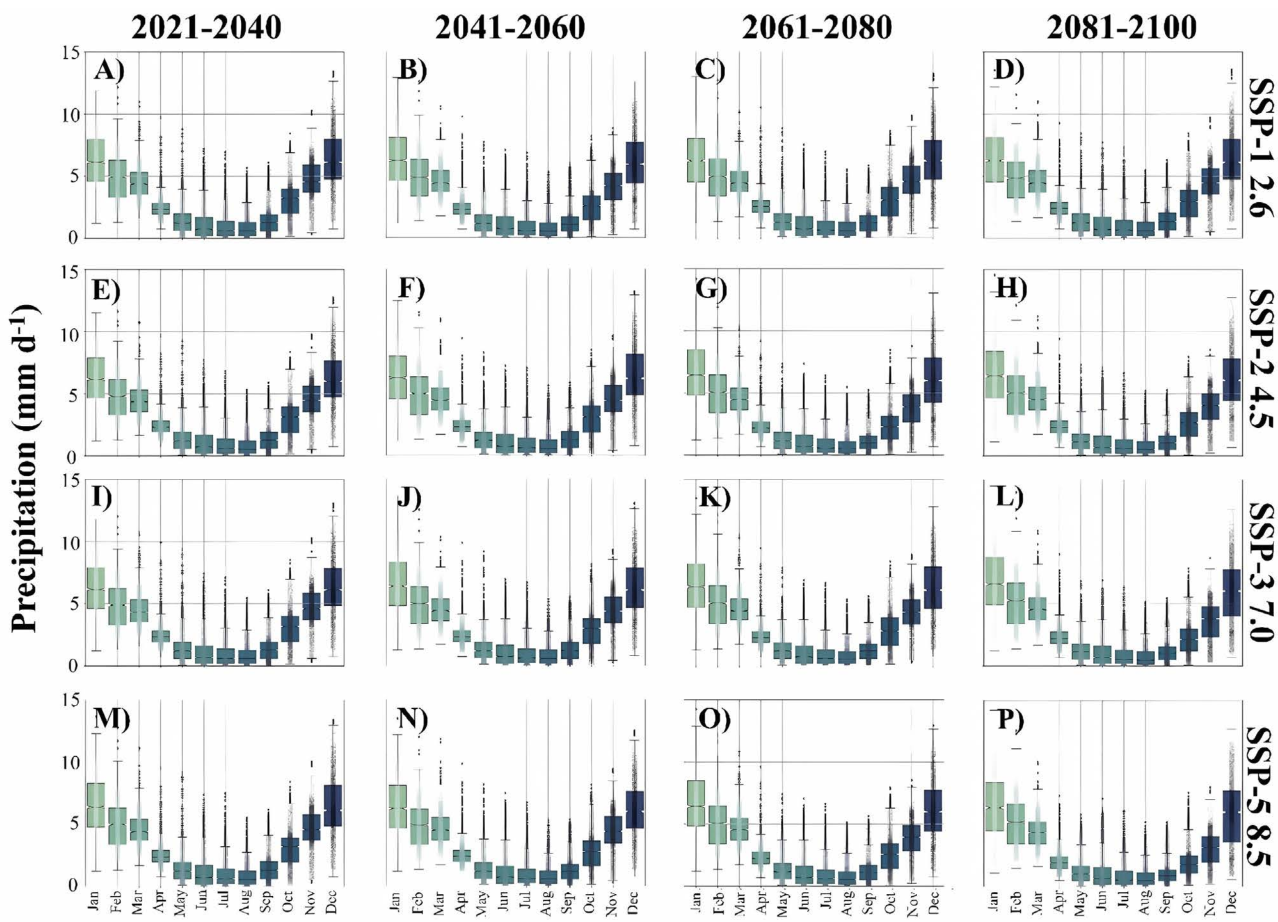

Figure 7 - Box plots representing the seasonal variation of daily precipitation data in different periods and climate change scenarios: A) Period: 2021-2040 and Scenario: SSP-1 2.6; B) Period: 2041-2060 and Scenario: SSP-1 2.6; C) Period: 2061-2080 and Scenario: SSP-1 2.6; D) Period: 2081-2100 and Scenario: SSP-1 2.6; E) Period: 2021-2040 and Scenario: SSP-2 4.5; F) Period: 2041-2060 and Scenario: SSP-2 4.5; G) Period: 2061-2080 and Scenario: SSP-2 4.5; H) Period: 2081-2100 and Scenario: SSP-2 4.5; I) Period: 2021-2040 and Scenario: SSP-3 7.0; J) Period: 2041-2060 and Scenario: SSP-3 7.0; K) Period: 2061-2080 and Scenario: SSP-3 7.0; L) Period: 2081-2100 and Scenario: SSP-3 7.0; M) Period: 2021-2040 and Scenario: SSP-5 8.5; N) Period: 2041-2060 and Scenario: SSP-5 8.5; O) Period: 2061-2080 and Scenario: SSP-5 8.5; P) Period: 2081-2100 and Scenario: SSP-5 8.5.

this period of coffee phenology, determining the final productivity (Arcila-Pulgarin *et al*., 2002).

The municipalities with the highest Arabica coffee production are located in the state of Minas Gerais: Patrocínio (76,204 tons), Campos Gerais (59,275 tons), and Três Pontas (42,149 tons) (IBGE, 2021). These localities did not show high favorability to the disease. They were classified as favorable only during October and March (Fig. 8). However, Manhuaçu-MG (36,826 tons) and Iúna-ES (30,000 tons) presented highly favorable conditions between October and December. These months concentrate the second phenological year of the coffee tree (reproductive), in which flowering and pinhead fruits (initial structure of fruits) occur. These two stages are very important, as they determine the amount of fruit produced (Drinnan and Menzel, 1995). Thus, preventive strategies should be used in localities such as Manhuaçu and Iúna to prevent the *Phoma* spp. attack from September onwards. The application of copper-derived solutions can induce the activation of the coffee plant's immune system, being a more sustainable management practice (Silva *et al*., 2019).

3.4. *Phoma* spp. favorability zoning and climate change

The variation between scenarios was subtle, standing out in Figs. 9 and 10 the most optimistic (SSP-1 2.6) and pessimistic (SSP-5 8.5) scenarios, respectively (Fig. 11). Favorable and highly favorable classes were reduced in both scenarios. Favorable regions presented means of 19.8% (SSP-1 2.6) and 18.5% (SSP-5 8.5). The mean in October for the highly favorable class was 5.3 and 5.2% for SSP-1 2.6 and SSP-5 8.5, respectively (Figs. 9 and 10).

The coffee-producing region of Brazil showed an increase in unfavorable areas to phoma leaf spot in both scenarios. The increase in the unfavorable class was visible during all months. The means of the unfavorable class were 31.2% (SSP-1 2.6) and 34.1% (SSP-5 8.5). The relatively favorable class predominated for both SSP-1 2.6

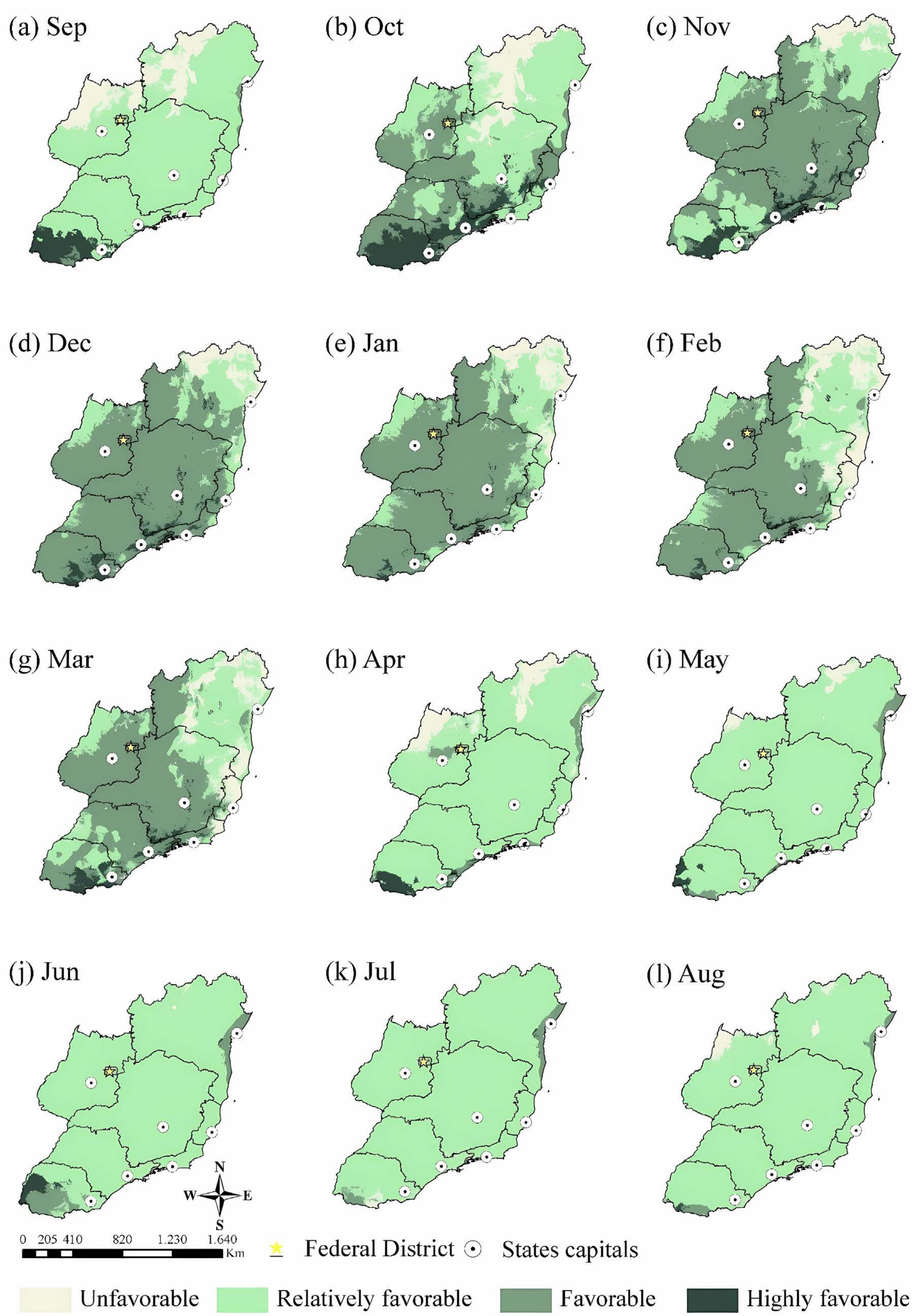

Figure 8 - *Phoma* spp. favorability zoning spatialization for each month of coffee phenology in the actual scenario. A) September; B) October; C) November; D) December; E) January; F) February; G) March; H) April; I) May; J) June; K) July; L) August.

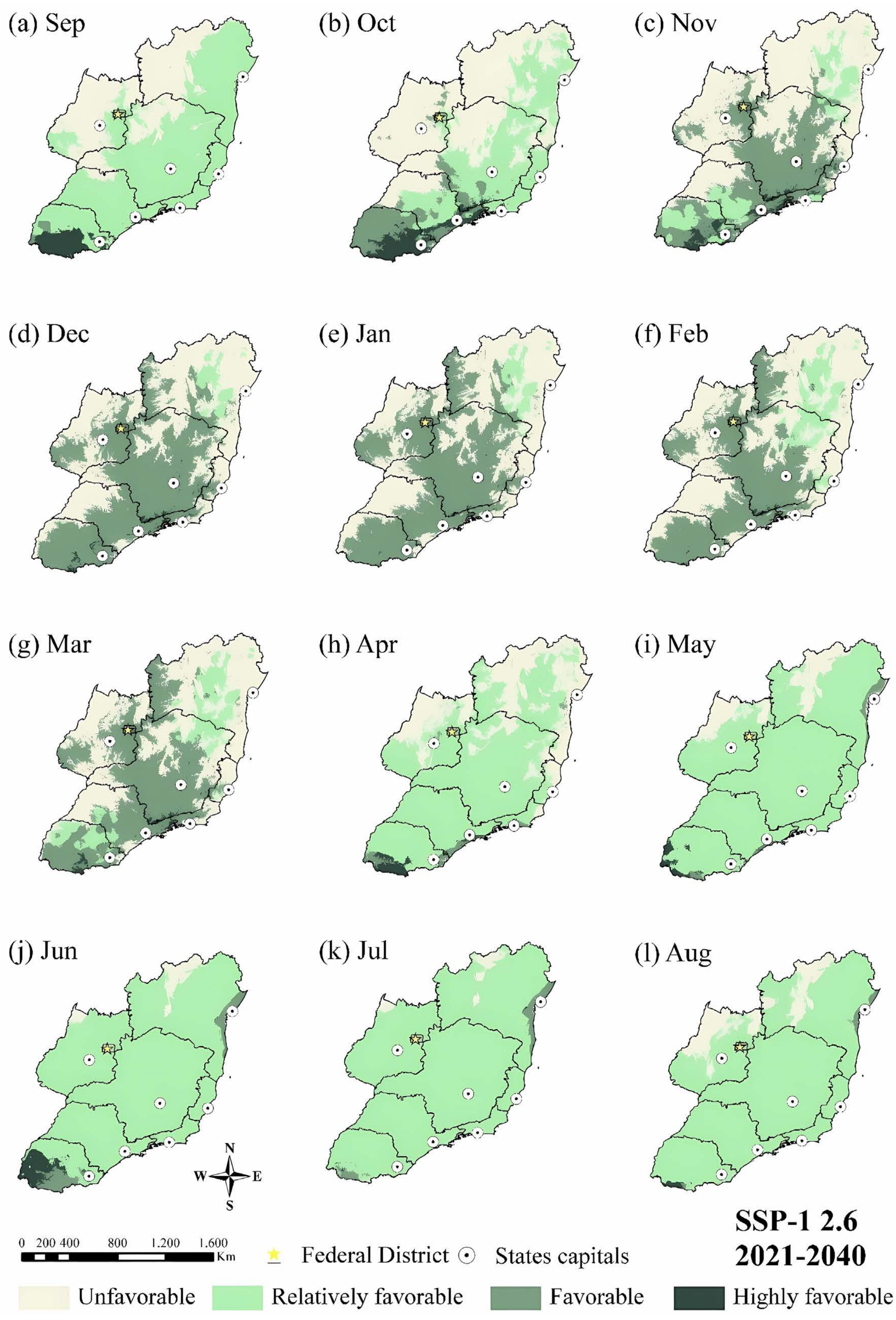

Figure 9 - *Phoma* spp. favorability zoning spatialization for each month of coffee phenology in the SSP-1 2.6 scenario during the period 2021-2040. A) September; B) October; C) November; D) December; E) January; F) February; G) March; H) April; I) May; J) June; K) July; L) August.

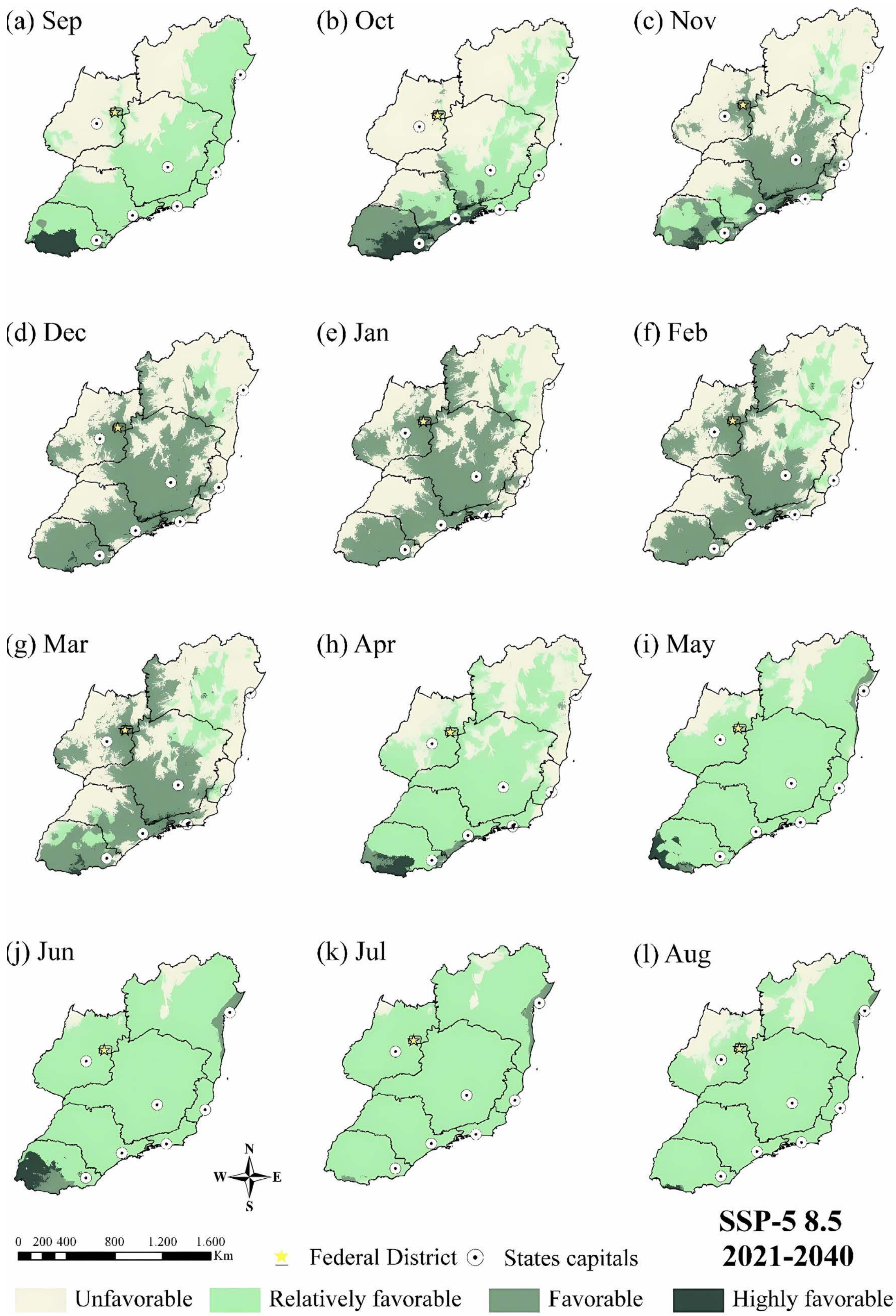

Figure 10 - *Phoma* spp. favorability zoning spatialization for each month of coffee phenology in the SSP-5 8.5 scenario during the period 2021-2040. A) September; B) October; C) November; D) December; E) January; F) February; G) March; H) April; I) May; J) June; K) July; L) August.

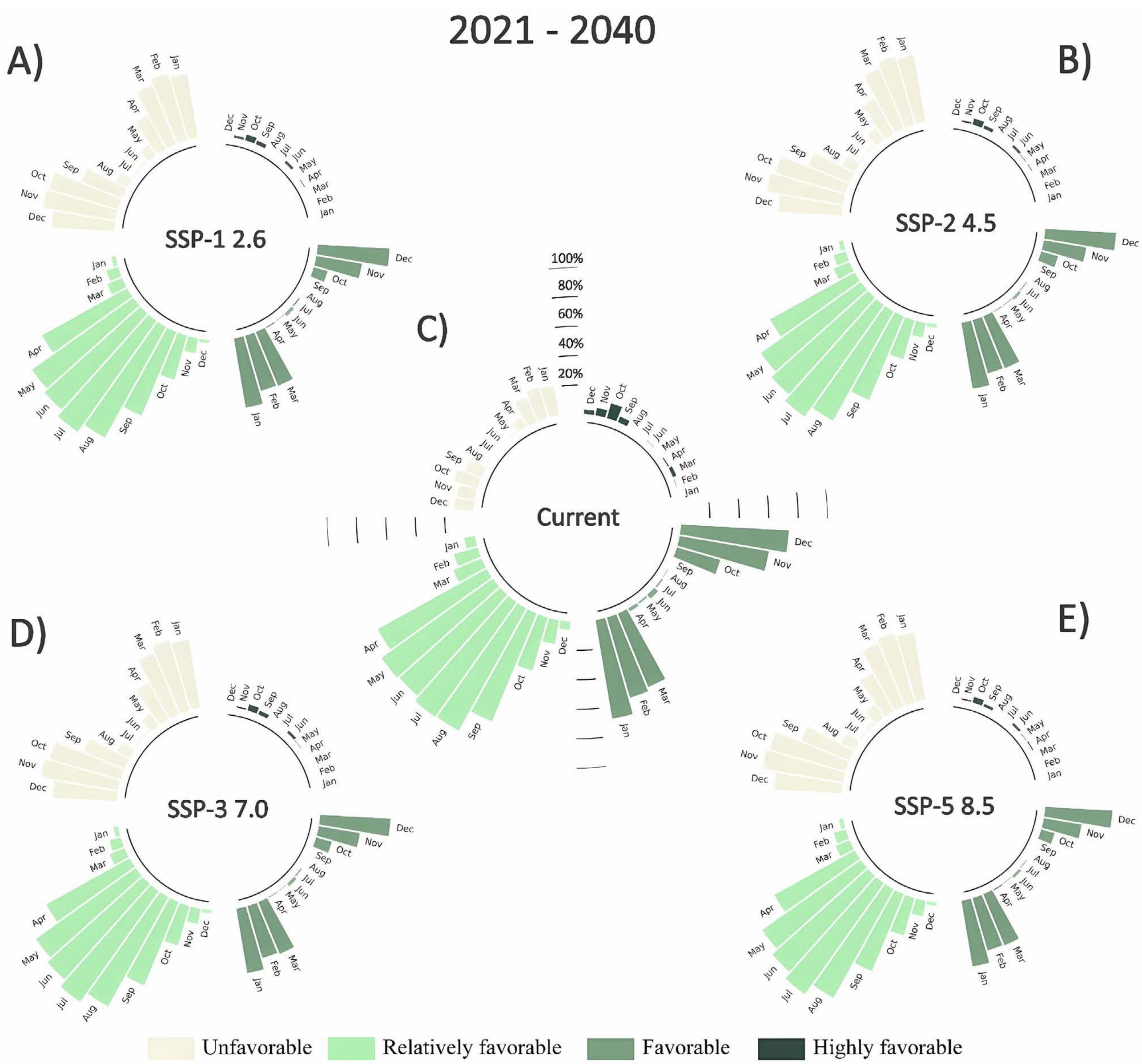

Figure 11 - Seasonal distribution of the concentration of each *Phoma* spp. favorability zoning class for the current scenario (C), SSP-1 2.6 (A), SSP-2 4.5 (B), SSP-3 7.0 (D), and SSP-5 8.5 (E) in 2021-2040.

(47.3%) and SSP-5 8.5 (45.9%). June and July presented the lowest alterations from climate change (Fig. 10).

Some states showed higher variation in zoning due to climate change. Goiás presented 56.8% (SSP-1 2.6) and 61.3% (SSP-5 8.5) of the territory classified as unfavorable from September to March. On the other hand, the state of Paraná did not show areas classified as unfavorable. The means in the state for the highly favorable class were 12.9% (SSP-1 2.6) and 13.4% (SSP-5 8.5). An increase in the areas most favorable to the development of phoma leaf spot occurred in June in the south of Paraná.

Climate changes in 2041-2060 showed more impact on areas suitable for *Phoma* spp. development. All scenarios showed alterations in the zoning classes (Fig. 12). However, significant changes between scenarios were observed during 2041-2060. The unfavorable class in the most optimistic SSP-1 2.6 scenario had a mean of 37.9% (Fig. 12). In contrast, the mean unfavorable area was 51.3% in the SSP-5 8.5 scenario (Fig. 13). The period from October to March was more affected in both scenarios. On the other hand, June and July were less affected, with 92.02% (SSP-1 2.6) and 87.3% (SSP-5 8.5) of the territory being relatively favorable (Fig. 14).

Some states underwent major changes in the climatic zoning for phoma leaf spot (Figs. 12 and 13). The state of Paraná increased highly favorable areas in June, with mean values of 28.9% (SSP-1 2.6) and 37.9% (SSP-5 8.5). On the other hand, the state of Bahia did not show the

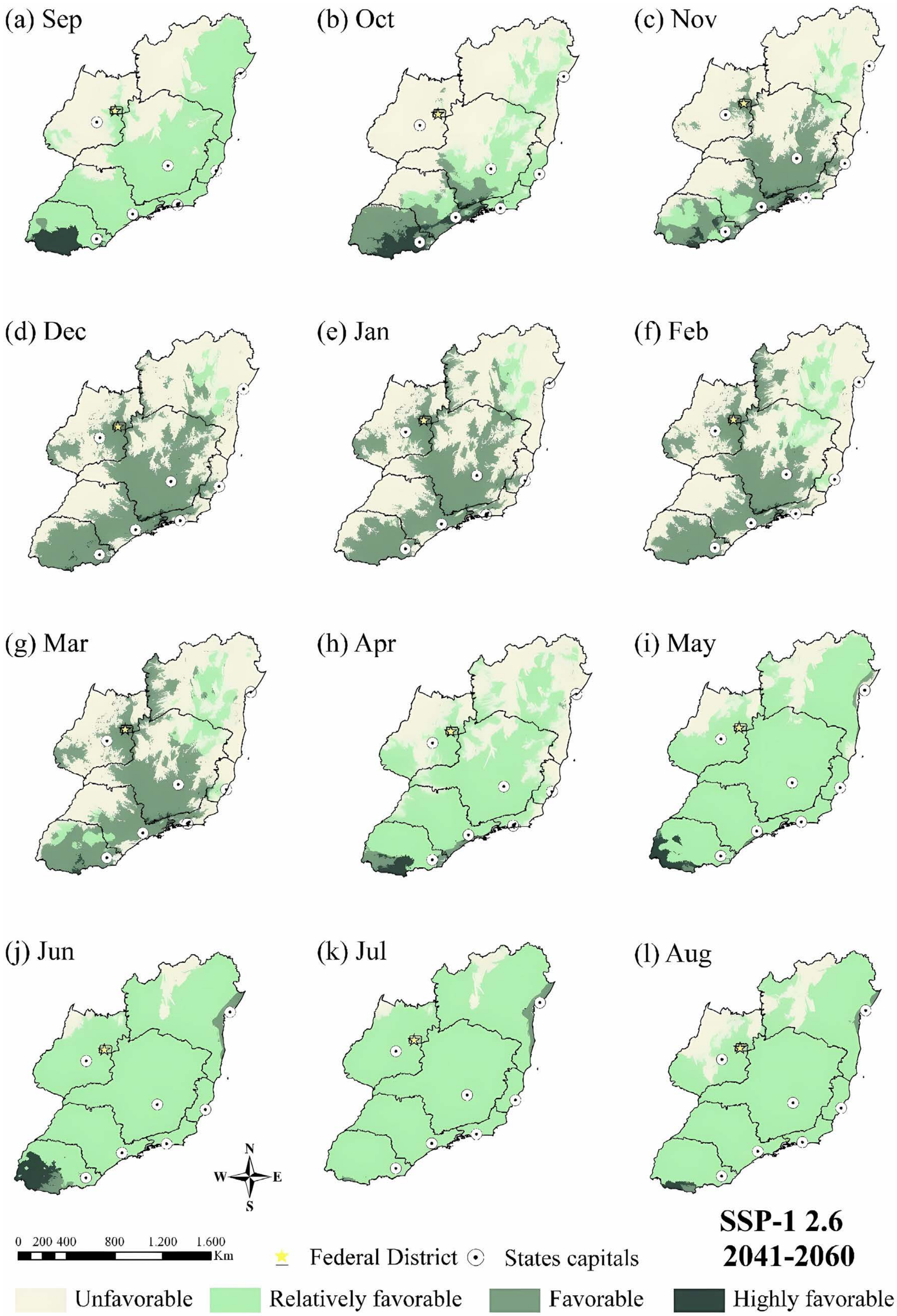

Figure 12 - *Phoma* spp. favorability zoning spatialization for each month of coffee phenology in the SSP-1 2.6 scenario during the period 2041-2060. A) September; B) October; C) November; D) December; E) January; F) February; G) March; H) April; I) May; J) June; K) July; L) August.

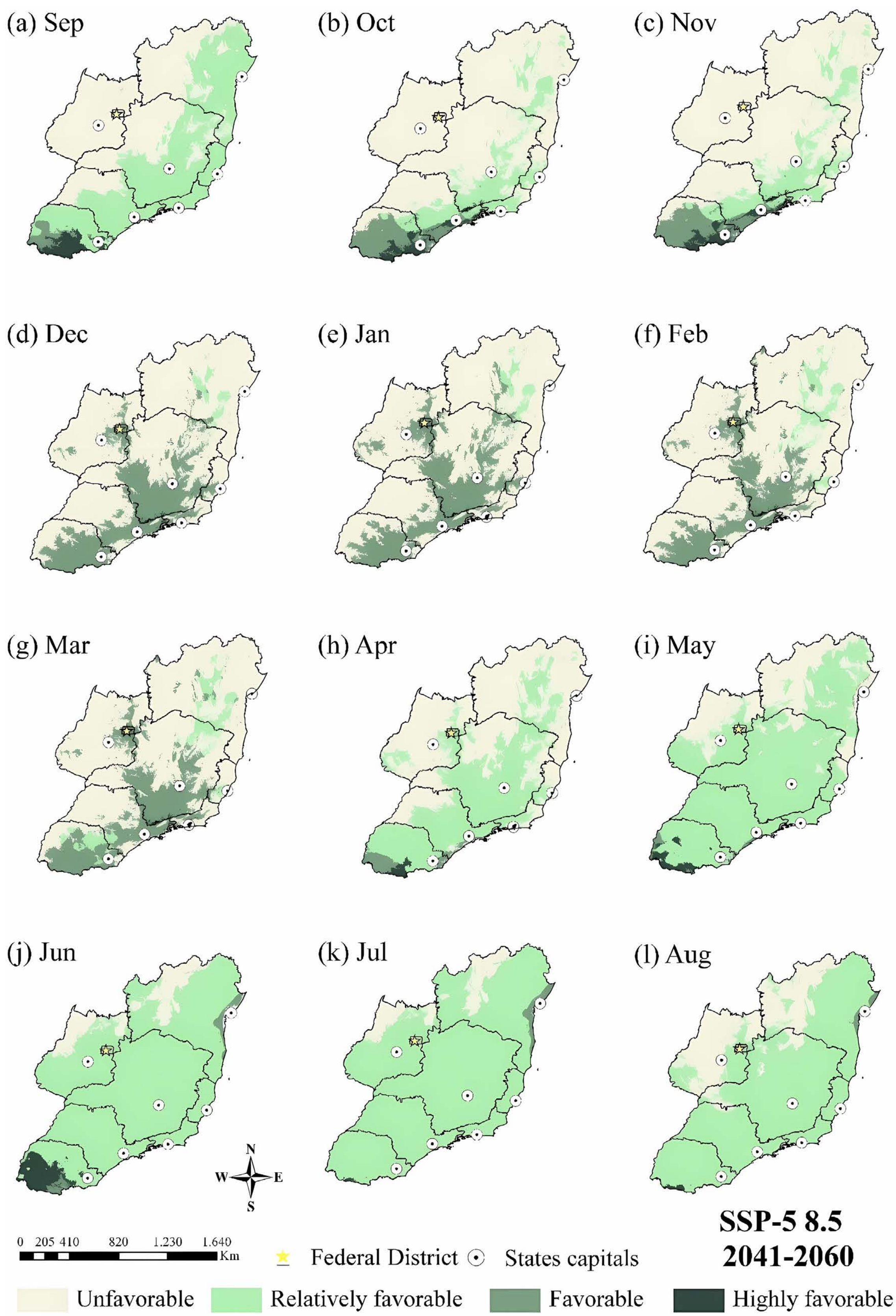

Figure 13 - *Phoma* spp. favorability zoning spatialization for each month of coffee phenology in the SSP-5 8.5 scenario during the period 2041-2060. A) September; B) October; C) November; D) December; E) January; F) February; G) March; H) April; I) May; J) June; K) July; L) August.

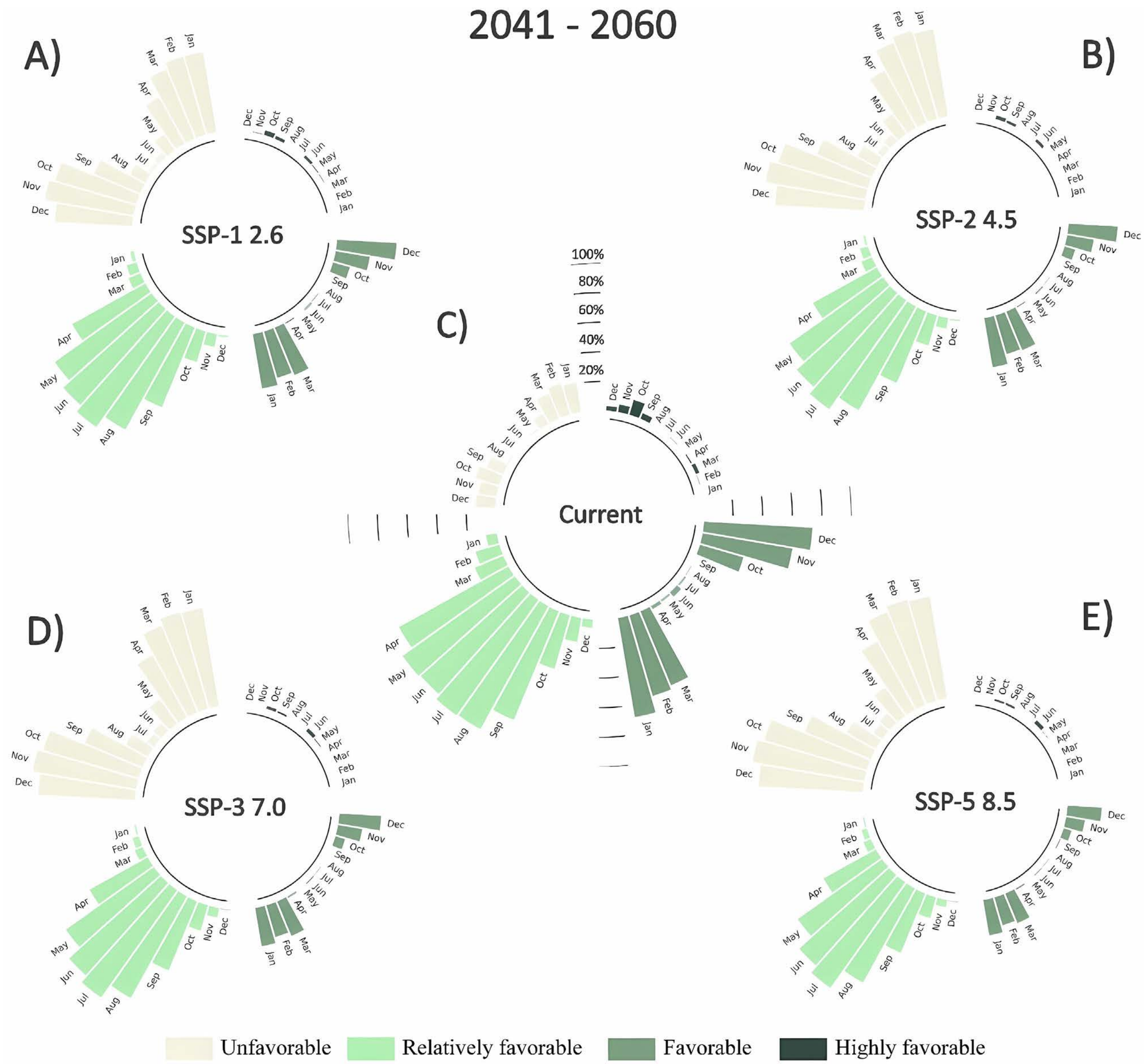

Figure 14 - Seasonal distribution of the concentration of each *Phoma* spp. favorability zoning class for the current scenario (C), SSP-1 2.6 (A), SSP-2 4.5 (B), SSP-3 7.0 (D), and SSP-5 8.5 (E) in 2041-2060.

highly favorable class. The predominant class in Bahia was unfavorable, reaching 53.6% (SSP-1 2.6) and 66.3% (SSP-5 8.5). Only the coast of Bahia presented the favorable class between June and August. The state of Goiás presented 100% of its territory not favorable to the disease between September and November (Fig. 13).

The climate zoning for phoma leaf spot in 2061-2080 varied as a function of the scenario. SPP-1 2.6 showed means of 43.6 and 38.7% for the relatively favorable and unfavorable classes, respectively. The mean of favorable areas was 16.2%. Favorability to the disease was observed in the producing regions from November to March (Fig. 15c, d, r, f, and g). The predominant class during the coldest months (May to August) was relatively favorable (88.3%). According to Salgado *et al.* (2003), mild air temperatures favor *Phoma* spp. development.

SSP-5 8.5 had a high reduction of areas favorable to *Phoma* spp. development (Fig. 16). The mean for the favorable class between October and March was 8.4%. The states of Goiás and Bahia obtained means of 90.7 and 82.1%, respectively. However, the state of Paraná increased its favorable area in June (26.4%).

Climate changes in 2081-2100 showed the highest alterations in the *Phoma* spp. favorability zoning. Both scenarios reduced the areas favorable to phoma leaf spot. Highly favorable areas became scarce, that is, only 1.5% (SSP-1 2.6) and 0.3% (SSP-5 8.5) of the region. Favorable areas in SSP-1 2.6 were concentrated from October to

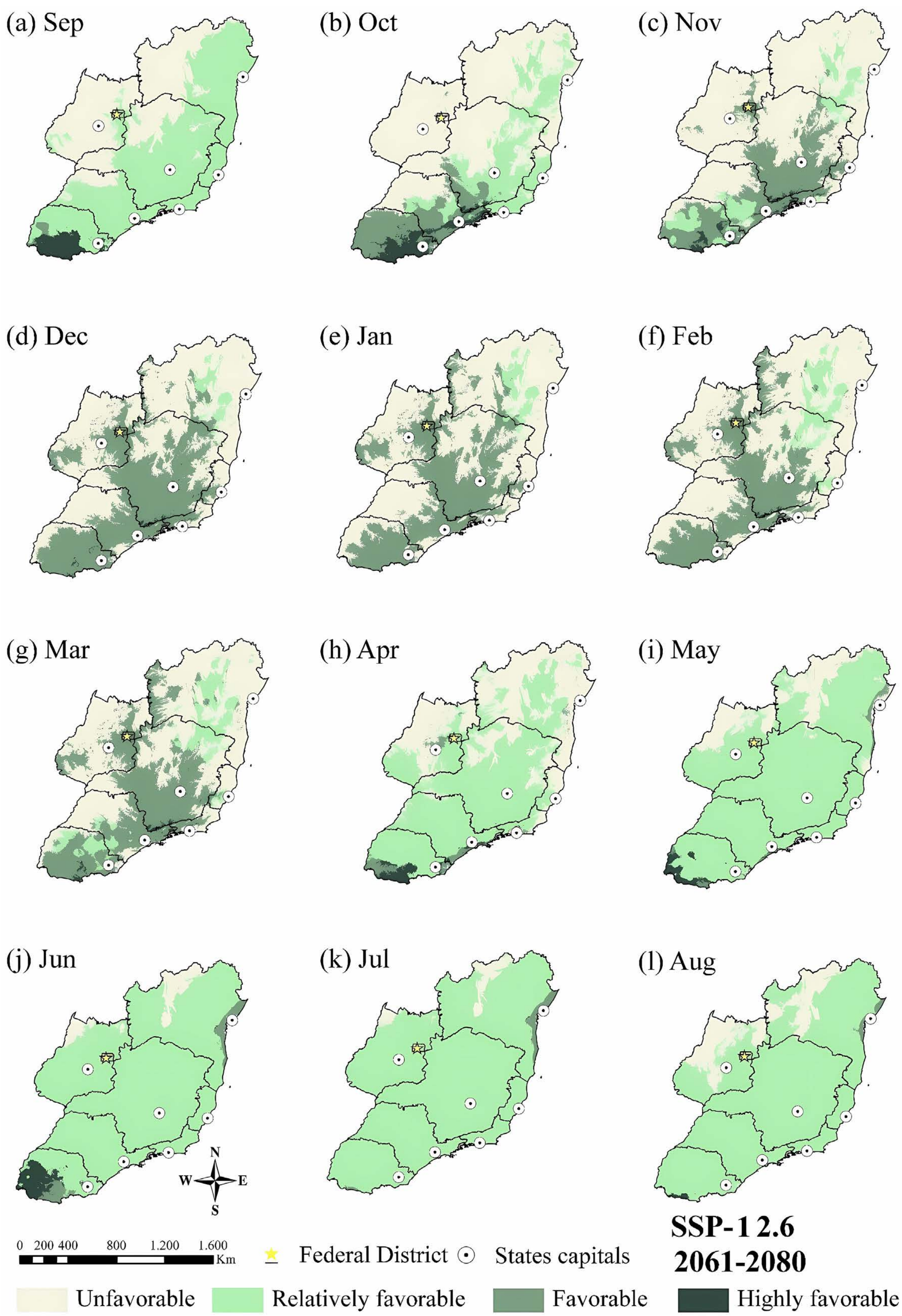

Figure 15 - *Phoma* spp. favorability zoning spatialization for each month of coffee phenology in the SSP-1 2.6 scenario during the period 2061-2080. A) September, B) October, C) November, D) December, E) January, F) February, G) March, H) April, I) May, J) June, K) July, L) August.

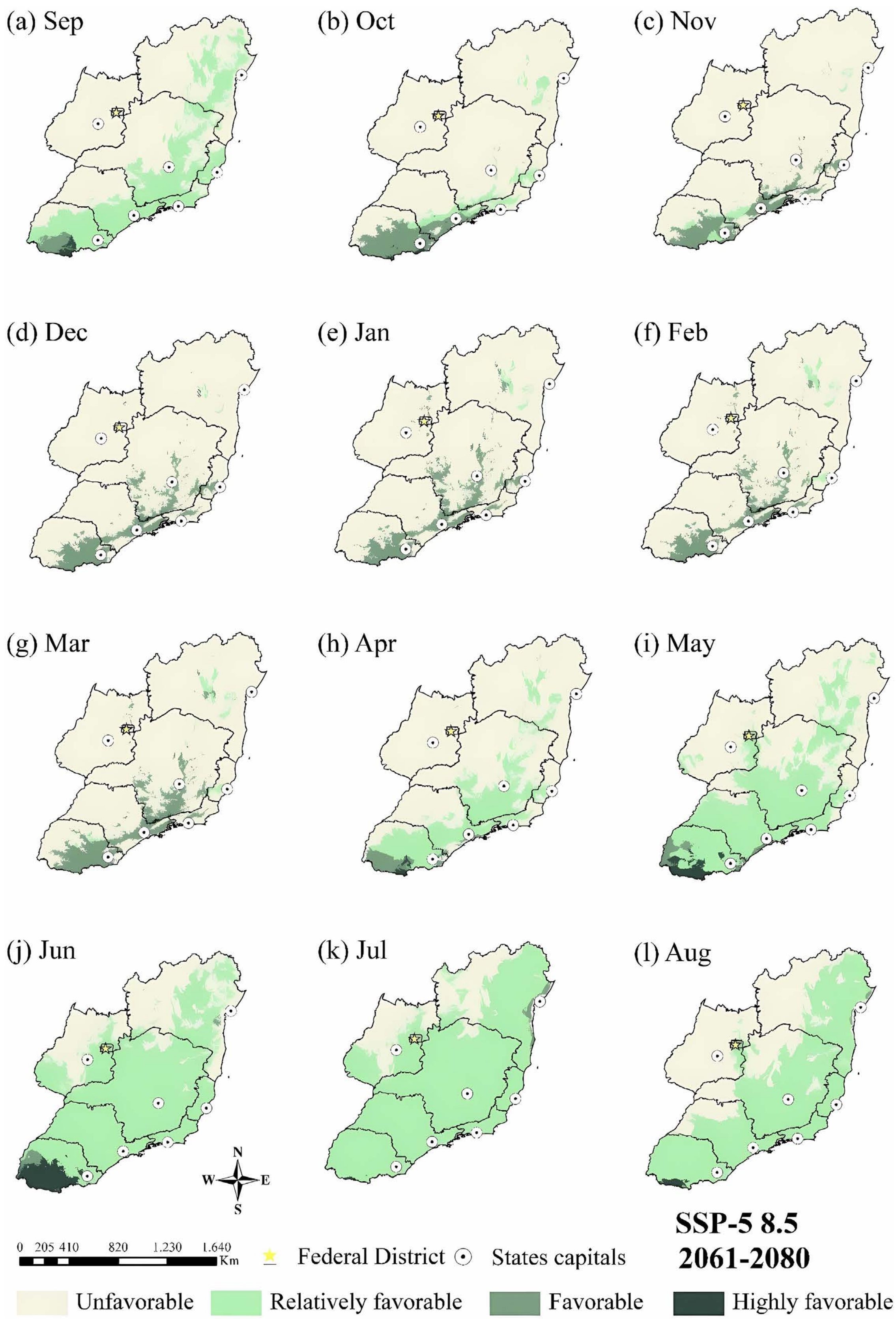

Figure 16 - *Phoma* spp. favorability zoning spatialization for each month of coffee phenology in the SSP-5 8.5 scenario during the period 2061-2080. A) September; B) October; C) November; D) December; E) January; F) February; G) March; H) April; I) May; J) June; K) July; L) August.

March (Fig. 17b, c, d, e, f, and g). Minas Gerais presented favorable conditions (51.4%) from November to March. The SSP-1 2.6 scenario showed low variation for regions with high coffee production, regardless of the period (Fig. 18). This scenario is considered the most optimistic (SSP-1 2.6), also showing a low variation in favorability zoning for phoma leaf spot in Minas Gerais.

The SPP-5 8.5 scenario drastically changed the favorability zoning for phoma leaf spot in 2081-2100. The class favorable to the development of the disease (1.8%) represents little of the region. Most areas were classified as unfavorable (around 85.0%). There was an inversion of the periods most favorable to the disease relative to the current scenario. The unfavorable class had a mean of 97.3% between October and March. On the other hand, June and July had the highest risk of disease attack. The mean of the relatively favorable class during these months was 41.4% (Fig. 19).

The unfavorable class predominated in all states. Goiás presented 99.0% of its area classified as unfavorable. The southwest of Bahia showed no favorability for *Phoma* spp. throughout the year. Likewise, the unfavorable class predominated in the northeast region of São Paulo, reaching 75.2% of the entire state. These regions are highly suitable for growing Arabica coffee (Assad *et al*., 2000). In contrast, the state of Paraná showed high

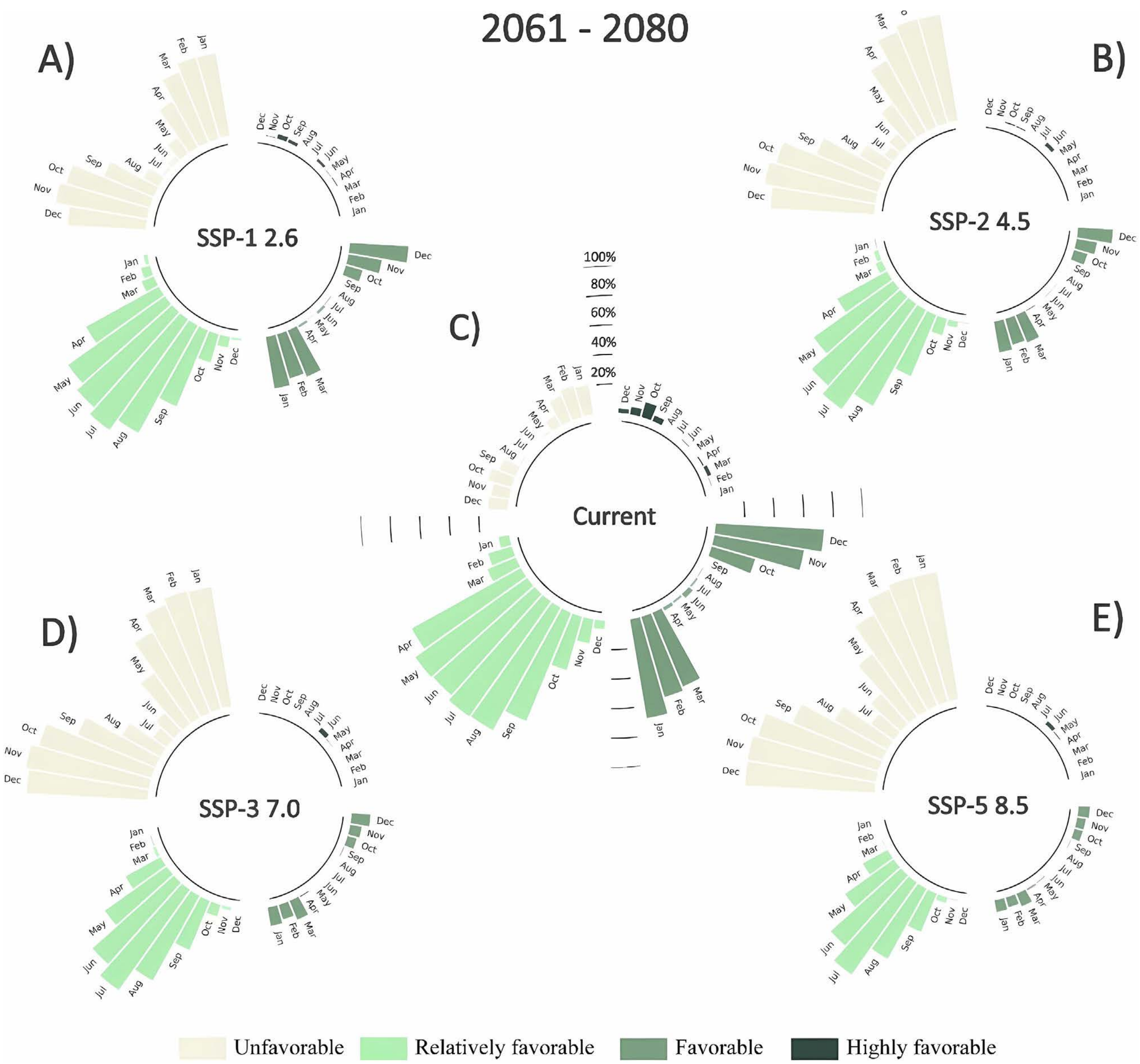

Figure 17 - Seasonal distribution of the concentration of each *Phoma* spp. favorability zoning class for the current scenario (C), SSP-1 2.6 (A), SSP-2 4.5 (B), SSP-37.0 (D), and SSP-5 8.5 (E) in 2061-2080.

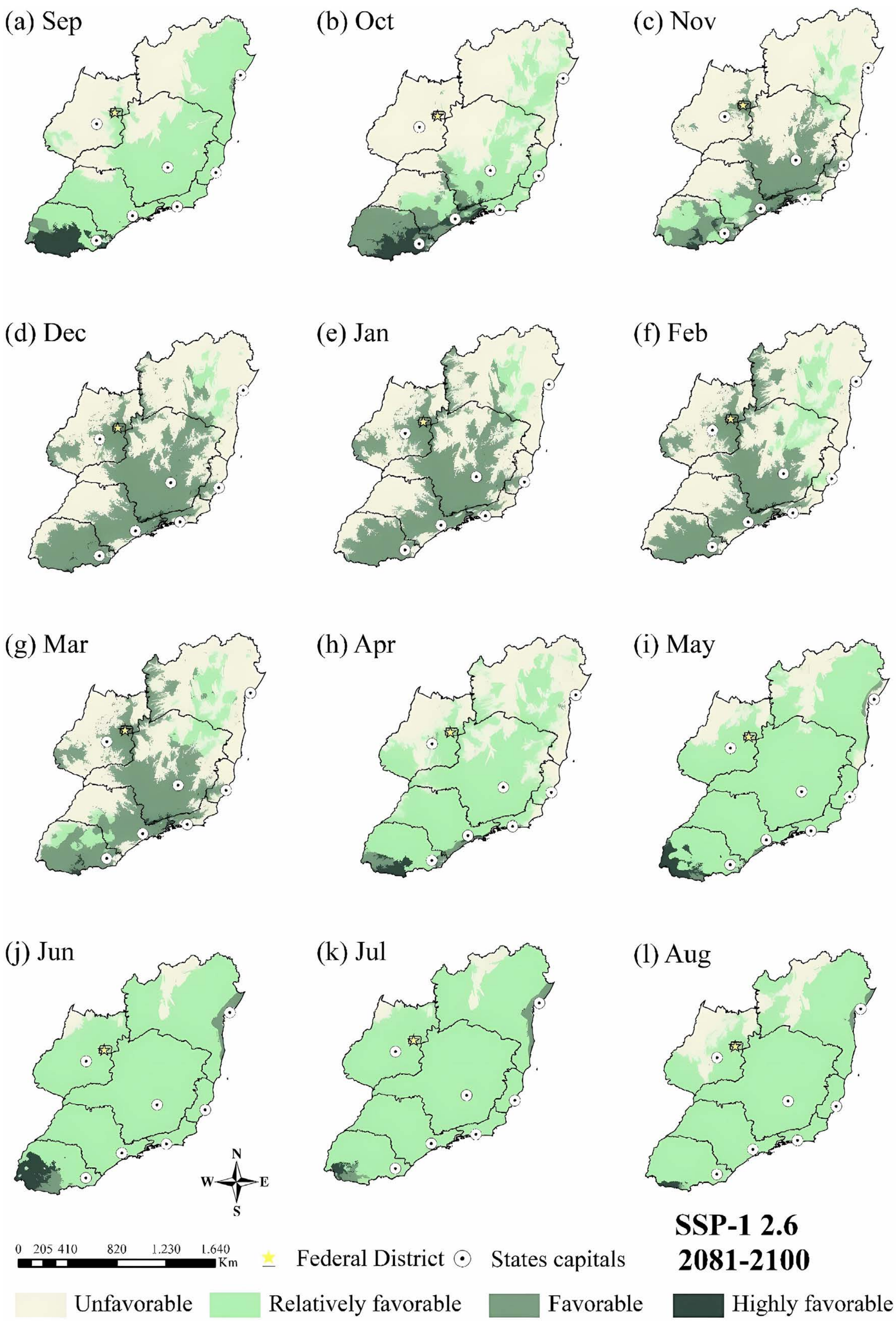

Figure 18 - *Phoma* spp. favorability zoning spatialization for each month of coffee phenology in the SSP-1 2.6 scenario during the period 2081-2100. A) September; B) October; C) November; D) December; E) January; F) February; G) March; H) April; I) May; J) June; K) July; L) August.

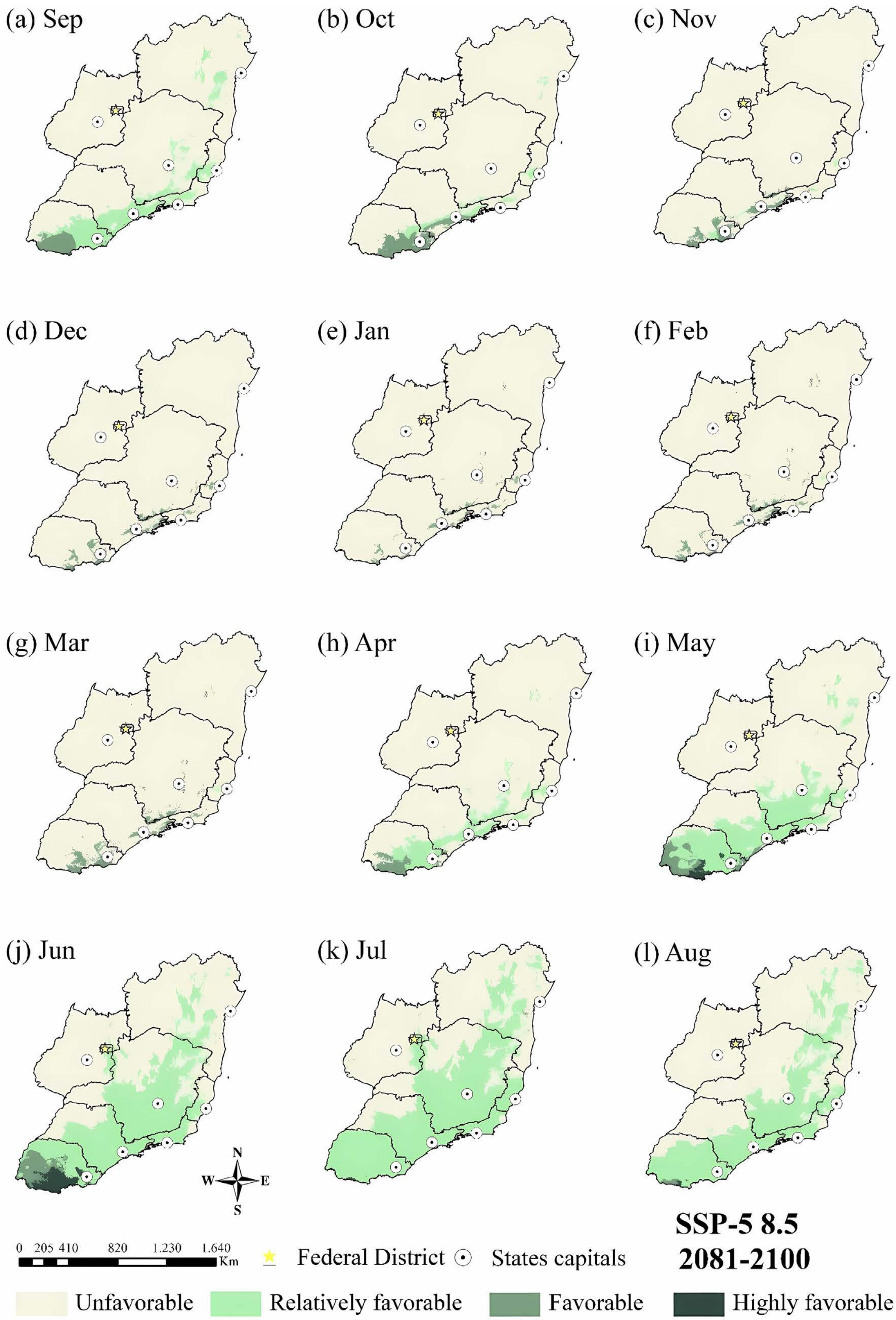

Figure 19 - *Phoma* spp. favorability zoning spatialization for each month of coffee phenology in the SSP-5 8.5 scenario during the period 2081-2100. A) September; B) October; C) November; D) December; E) January; F) February; G) March; H) April; I) May; J) June; K) July; L) August.

favorability to the disease during June (23.5%), but only in the south of the state, a region where coffee is not grown.

Climate change (SSP-5 8.5) reduced the presence of phoma leaf spot in coffee plantations in Minas Gerais in all months (Fig. 19). The unfavorable class showed a mean of 83.2% of the state of Minas Gerais. Moreover, the relatively favorable class only predominated in June (57%) and July (63.6%) (Fig. 20). Localities such as Patrocínio, Campos Gerais, Três Pontas, Manhuaçu, and Iúna did not show favorability between October and April. These municipalities showed climate conditions relatively favorable to the disease from May to June. Thus, climate changes reduced the occurrence of phoma leaf spot in the main producing localities. Bebber (2019) studied black Sigatoka (*Pseudocercospora fijiensis*), the main banana disease. The study also reported a reduction in favorable areas for the disease across Latin America.

3.5. *Phoma* spp. favorability zoning variation for each scenario in different periods

Figure 20 summarizes the results find in the present study. It shows that climate changes will affect the presence of *Phoma* spp. in coffee plantations in all scenarios. All scenarios show that the climate conditions become more unfavorable for the incidence of *Phoma* spp. over the years. For instance, the most optimistic IPCC scenario

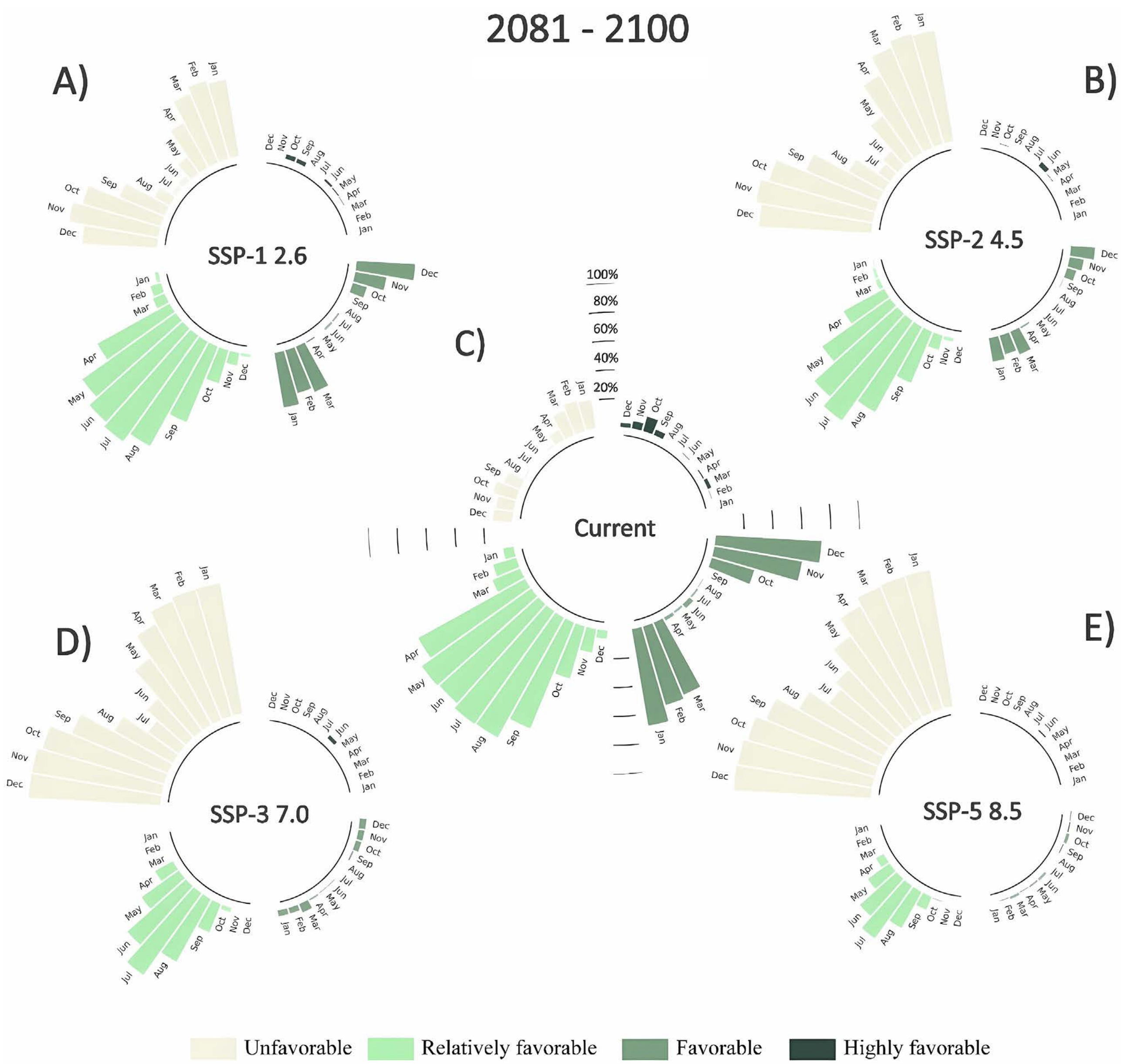

Figure 20 - Seasonal distribution of the concentration of each *Phoma* spp. favorability zoning class for the current scenario (C), SSP-1 2.6 (A), SSP-2 4.5 (B), SSP-3 7.0 (D), and SSP-5 8.5 (E) in 2081-2100.

(SSP-1 2.6) under the current climate condition has 31.2% of the region's area in the unfavorable class. In contrast, this unfavorable class predominates in 38.0% of the entire region in the period 2081-2100 (Fig. 21a).

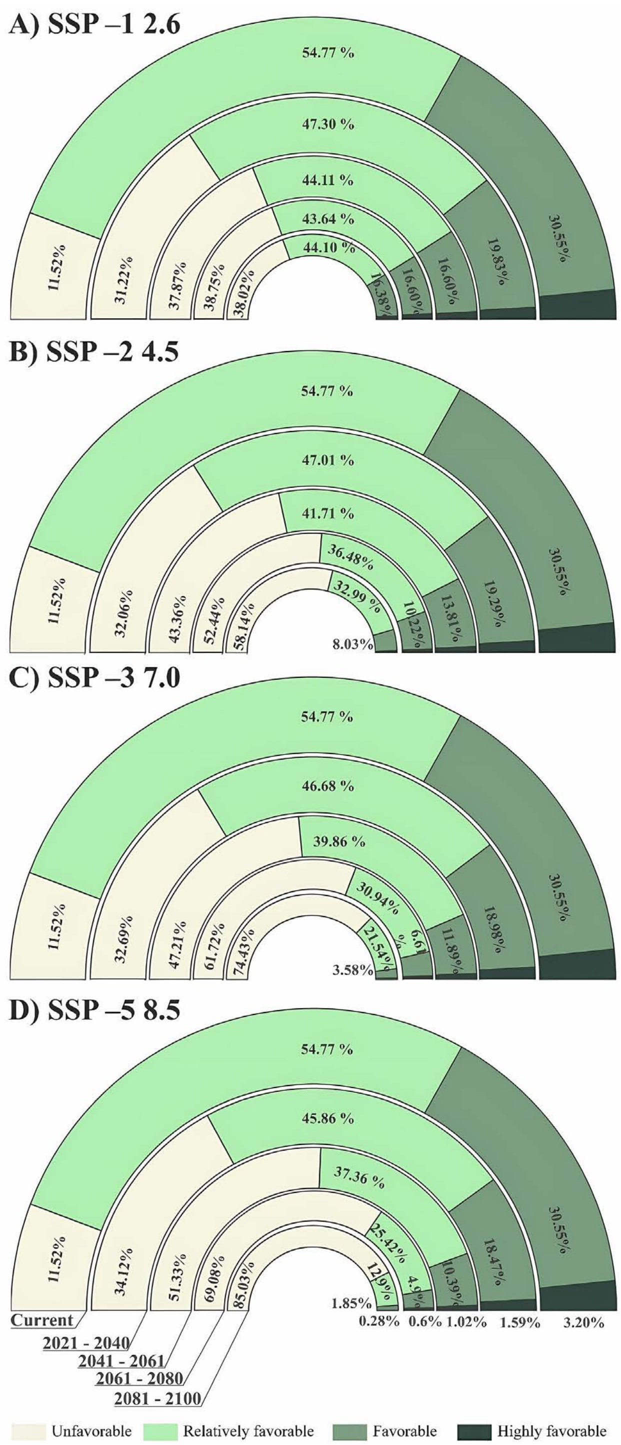

Figure 21 - Comparison of favorability zoning for *Phoma* spp. during all periods (current, 2021-2040, 2041-2060, 2061-2080, and 2081-2100) for scenarios SSP-1 2.6 (A), SSP-2 4.5 (B), SSP-3 7.0 (C), and SSP-5 8.5 (D).

The most pessimistic scenario (SSP-5 8.5) demonstrated an increase in areas unfavorable to phoma leaf spot even in the short term (2021-2040). On the other hand, about 85.0% of the entire coffee-producing region was unfavorable to the disease in the long term (2081-2100) (Fig. 21d). In this scenario, the presence of phoma leaf spot is reduced, facilitating the management of coffee plantations and reducing most of the costs. However, fungi are easily selected by the environment (Desprez-Loustau *et al*., 2007). Zhan and McDonald (2011) reported that the increase in temperature selects more resistant individuals of the fungus *Mycosphaerella graminicola*. Therefore, climate changes may provide the selection of the most resistant *Phoma spp.* individuals.

The findings from this study revealed distinct patterns and trends, as showcased in the supplementary figures. Specifically, variations in the parameters analyzed can be distinctly observed in Supplementary Figs. S1 through S8. Some of these figures, especially those related to the climatic suitability zoning for Phoma, have been included in the annex for more detailed observation. A comprehensive understanding of the study's outcomes necessitates a thorough examination of these figures. The trends delineated within both the main and supplementary figures offer additional insights that bolster the primary conclusions drawn from the research.

4. Conclusions

The climate of the region features hot and rainy summers, with an annual mean air temperature of 21.6 °C and daily precipitation of 3.5 mm. Bahia has the highest mean air temperature and lowest daily rainfall among the states in the region. Climate change drastically alters the climate of the region. The mean air temperature in the long term (2081-2100) increases by 6.1 °C and daily precipitation decreases by 0.4 mm day^{-1}. Goiás becomes the hottest and rainiest state, while Bahia continues with a low rainfall rate. These changes affect the development of the fungus *Phoma* spp.

Regions with higher favorability for *Phoma* spp. can be identified through climate data. About 54.8% of the coffee-producing region has relatively favorable conditions for the development of phoma leaf spot, 30.5% favorable, 3.2% highly favorable, and 11.5% of the region demonstrates no climate conditions for the occurrence of the disease. Climate conditions from October to March favor the occurrence of phoma leaf spot. Localities such as Manhuaçu-MG and Iúna-ES are highly prone to the disease from October to December. Constant monitoring of the disease is necessary, especially from October to March.

In the future, the occurrence of *Phoma* spp. tend to be reduced due to the loss of favorable climate conditions in all scenarios. The most optimistic IPCC scenario (SSP-

1 2.6) in the short term (2021-2040) shows an increase of 19.7% in the area unfavorable to the disease. On the other hand, 85.0% of the entire region in the period 2081-2100 is unfavorable to the development of *Phoma* spp. for the most pessimistic scenario. Thus, Patrocínio, Campos Gerais, Três Pontas, Manhuaçu, and Iúna do not show favorability between October and April.

Thus, climate changes will provide unsuitable conditions for the development of *Phoma* spp., thus reducing the occurrence of the disease in coffee plantations. Importantly, the process of natural selection can lead to the selection of more resistant pathogen individuals. However, coffee may not adapt to the changes, which may negatively affect its production in Brazil.

Acknowledgments

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Internet Resources

WorldClim 2.1, https://www.worldclim.org/data/cmip6/cmip6_clim30s.html.

IPSL-CMC, https://cmc.ipsl.fr/.

QGIS, http://www.qgis.org/.

Supplementary Material

Figure S1 - Spatialization of favorability zoning for Phoma spp. for the period 2021-2040, SSP-2 4.5 scenario, for each month of coffee phenology. A) September, B) October, C) November, D) December, E) January, F) February, G) March, H) April, I) May, J) June, K) July, L) August.

Figure S2 - Spatialization of favorability zoning for Phoma spp. for the period 2021-2040, SSP-3 7.0 scenario, for each month of coffee phenology. A) September, B) October, C) November, D) December, E) January, F) February, G) March, H) April, I) May, J) June, K) July, L) August.

Figure S3 - Spatialization of favorability zoning for Phoma spp. for the period 2041-2060, SSP-2 4.5 scenario, for each month of coffee phenology. A) September, B) October, C) November, D) December, E) January, F) February, G) March, H) April, I) May, J) June, K) July, L) August.

Figure S4 - Spatialization of favorability zoning for Phoma spp. for the period 2041-2060, SSP-3 7.0 scenario, for each month of coffee phenology. A) September, B) October, C) November, D) December, E) January, F) February, G) March, H) April, I) May, J) June, K) July, L) August.

Figure S5 - Spatialization of favorability zoning for Phoma spp. for the period 2061-2080, SSP-2 4.5 scenario, for each month of coffee phenology. A) September, B) October, C) November, D) December, E) January, F) February, G) March, H) April, I) May, J) June, K) July, L) August.

Figure S6 - Spatialization of favorability zoning for Phoma spp. for the period 2061-2080, SSP-3 7.0 scenario, for each month of coffee phenology. A) September, B) October, C) November, D) December, E) January, F) February, G) March, H) April, I) May, J) June, K) July, L) August.

Figure S7 - Spatialization of favorability zoning for Phoma spp. for the period 2081-2100, SSP-2 4.5 scenario, for each month of coffee phenology. A) September, B) October, C) November, D) December, E) January, F) February, G) March, H) April, I) May, J) June, K) July, L) August.

Figure S8 - Spatialization of favorability zoning for Phoma spp. for the period 2081-2100, SSP-3 7.0 scenario, for each month of coffee phenology. A) September, B) October, C) November, D) December, E) January, F) February, G) March, H) April, I) May, J) June, K) July, L) August.