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## Ecological zoning of soybean rust, coffee rust and banana black sigatoka based on Brazilian climate changes

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### Abstract

Geoinformation techniques were applied to develop predictive models to study the areas of risk to soybean rust (*Phakopsora pachyrhizi* Sydow) in soybean (*Glycine max* L.); coffee leaf rust (*Hemileia vastatrix* Berk & Br) in coffee; and black Sigatoka (*Mycosphaerella fijiensis* var. *difformis*) in banana, considering Brazil's climatic characterization and the distribution of soybean, coffee and banana crops. Temperature and rainfall data were obtained for the period from 1950 to 2000, for which observational data are available, and of simulations for 2020, 2050 and 2080 using the SRES A2 climate change scenarios. Using principal components analysis, a single variable was generated based on 57 variables, in order to determine an index explaining 87%, 88% and 90% of the variability of soybean, coffee and banana crops, respectively, in municipal districts across Brazil. The climatic model was used to generate the zoning of the three plant diseases, using temperature and leaf wetness as input. Areas of favorability for the diseases were plotted against the main coffee, soybean and banana growing areas in Brazil. This methodology enabled the visualization of the changes in areas favorable for epidemics under possible future scenarios of climate change.

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## 1. Introduction

Human beings depend on the resources of the biosphere, such as food, fiber and water, for their survival. In accordance with these needs, approximately 12% of Earth's land surface is used for agroecosystems, which occupy 18 million km<sup>2</sup> [1, 2]. However, this utilization, together with other human actions (mega-urbanization, industrialization) has caused biosphere and environmental changes [3-5], which now threaten to reduce the availability of the vital resources.

Since the mid-eighteenth century, the burning of fossil fuels and biomass has produced anthropogenic greenhouse gases and aerosols in quantities affecting atmospheric composition (CO<sub>2</sub>, O<sub>3</sub>, CH<sub>4</sub>, N<sub>2</sub>O, H<sub>2</sub>O, etc.), impacting the filtering of solar radiation and energy balance [6, 7]. Since the late nineteenth century, the average temperature of Earth's surface increased by  $0.6 \pm 0.2$  °C, causing changes in atmospheric motion, precipitation and humidity [8], consequently affecting the world's agroecosystems [9]. In particular, studies have shown the effect of climate change on the geographical distribution of some host crops [10-12] and the progress of epidemics of plant diseases [13-17].

With regard to the physical factors, temperature and humidity are crucial climatic variables, which in combination influence the progression of plant disease [18, 19]. Generally, temperature is the environmental factor most often correlated with biological responses of plant disease studies [20], because it interferes with the initial processes of infection, colonization, sporulation, and pathogen survival, as well as the physiological processes of the plant, such as evapotranspiration, photosynthesis, cell metabolism, and others [21]. Moisture can also affect both pathogens and hosts, and consequently is an important factor in plant disease [22], typically being represented in epidemiological studies by the following variables: relative humidity, leaf wetness, rainfall and soil moisture [23]. In addition, moisture is essential for the germination and spread of pathogens [18].

The currently growing use of geographic information systems (GIS) means that disease ecological zoning can be made more efficiently than with traditional methods of analysis, which were often expensive and difficult to implement [24, 25]. Over the past 25 years, and especially over the past decade, applications of GIS, remote sensing and spatial analysis (spatial statistics, geostatistics, spatial distribution models) in epidemiological studies have increased the acquisition, storage, access, analysis and representation of spatial data, enabling a deeper understanding of the dynamics of factors that influence the occurrence of epidemics [25].

Thus, studies have been performed to characterize the effects of environment and host (*Glycine max* L.) in the progress of soybean rust (*Phakopsora pachyrhizi* Sydow) in soybean [26-28], which have made it possible to model, simulate and predict the disease [29-34]. In the case of coffee, studies have been performed in Brazil with Brazilian cultivars, aiming to understand the influence of climate and host plants (*Coffea arabica* L.) in the epidemiology of coffee rust (*Hemileia vastatrix* Berk & Br) [21, 35-39]. In their study of banana plantations in Honduras, Jacome & Schuh [40] used multiple regression to describe the interaction of temperature, leaf wetness and leaf age on infection of two strains of black Sigatoka disease (*Mycosphaerella fijiensis* var. *difformis*). Using information on the effects of the environment on epidemics, the occurrence of disease can be modelled, simulated and predicted [37, 41], enabling the formulation of response strategies, setting control tactics in geographic regions where disease is not yet reported [42, 43] and verifying disease progression through space and time [44, 45], including under the influence of global climatic changes [46-49].

In this study, in order to help reduce the serious technical and economic losses that threaten the profitability of producers and the economy of the municipal districts of Brazil, geoscience and statistical techniques have been applied to develop predictive models to identify areas at risk of soybean rust, coffee rust and banana black Sigatoka in Brazil, according to the regional climatic characterization and the distributions of soybean, coffee and banana crops in the period of observed climate data, from the year

1950 to 2000, and under the effect of simulations of future climate change scenarios, for the years 2020, 2050 and 2080.

## 2. Methods

Modelling techniques based on nonlinear regression were used to characterize the monocyclic process of soybean rust, coffee rust and black Sigatoka of banana, using data obtained from [50], [51] and [40], respectively. Data on production (metric tons), harvested area (hectares) and planted area (hectares) of soybean, coffee and banana crops for the period from 1990 to 2008 were obtained from the Brazilian Institute of Geography and Statistics (IBGE). For climate information, the database used [52] provided high resolution climatic interpolated surfaces of mean air temperature and annual rainfall from the period from 1950 to 2000, and the A2 scenario of climate change, for the years 2020, 2050 and 2080.

Given the lack of models for the estimation of humidity, the climatic water balance and moisture index were calculated using a 30-year time series of climatic variables measured at 39 major meteorological stations belonging to the National Institute of Meteorology (INMET) of Minas Gerais state (Brazil, 1992) [53, 54], adopting evapotranspiration data estimated by the FAO Penman-Monteith method [55] and taking the available water capacity in the soil as 100 mm, the most usual in climatological studies [56]. The monthly climatological measures used were the mean, maximum and minimum temperature ( $^{\circ}\text{C}$ ), relative humidity (%), atmospheric pressure (mb), wind speed ( $\text{m s}^{-1}$ ), sunshine hours (h), rainfall (mm), and the reference evapotranspiration estimated by the FAO-Penman-Monteith method (mm). The annual water deficiency (mm) and water surplus were generated to estimate the aridity index, the humidity index and the Thornthwaite annual moisture index.

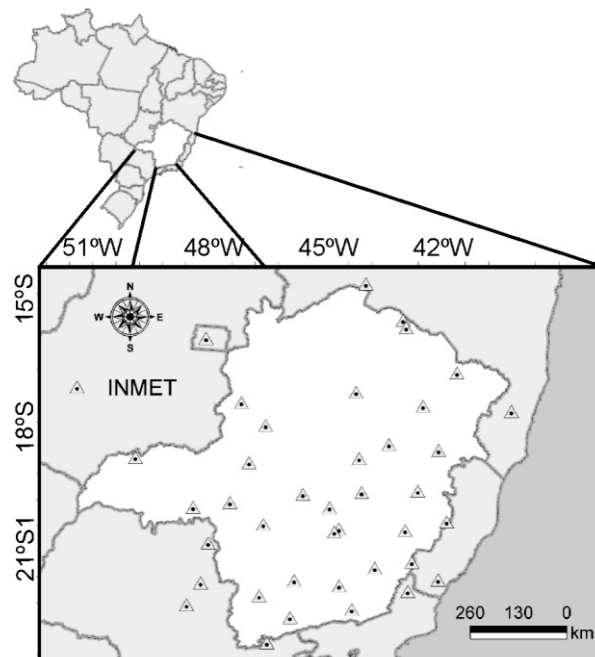


Fig. 1 Political boundary line of Minas Gerais state, showing the locations of INMET climatological stations used to develop the moisture index model.

Using the available data for temperature and precipitation, the moisture index was estimated within Brazil's boundary according to the model developed by Alves and Carvalho [57], giving an  $R^2$  of 0.92 for the state of Minas Gerais. This model was adopted because Minas Gerais presented all the climatic regimes outlined by Thornthwaite [53], in accordance with the model.

Similarly, there is a lack of models to estimate leaf wetness, so the moisture index was used to generate the leaf wetness, based on the observed relationship between monthly average duration of relative humidity higher than or equal to 90% and the moisture content of each month, taken from the database of Lavras station, in Minas Gerais. Continuous periods with the specified values of relative humidity were extracted from thermo-hygrograms for the period of 2000 to 2006.

The projections of climate change considered in the study are derived from a hierarchy of models based on climate, environment, land use, socioeconomic and technological aspects, coupled to indicate global responses and regional patterns of climate change [58]. It should be emphasized that these scenarios vary according to the degree of anthropogenic interference in the environment [59]. A2 is the scenario that describes a future world where very heterogeneous regionalization is dominant. There would be a strengthening of regional cultural identities, with emphasis on family values and traditions. Other features include high population growth and low economic and technological development.

A geographic information system was used to map areas favorable to the occurrence of these diseases, based on the relationship between climatic variables and the monocyclic process of the epidemics. Similarly, these techniques were used to characterize the spatial and temporal variability of the main production regions of soybean, coffee and bananas in Brazil, as well as the climate of these regions.

Principal component analysis was used as a data compression algorithm to characterize Brazilian municipal district data of soybean, coffee and banana yield, harvest, and cultivated areas [60]. For each crop,  $Z$  was determined as an  $n \times N$  matrix, in which  $n=57$  variables related to 19 years each of data for crop yield, crop harvested, and crop cultivated areas, and  $N$  spatially correlated samples in each of 5,564 municipal districts. The principal components matrix  $Y$  was also of size  $n \times N$ . Taking  $M$  of the  $N$  principal components, which explains an amount of the total variance in an  $n \times M$  matrix  $\tilde{Y}$ , the following approximation was obtained [61]:

$$\tilde{Z} \cong \tilde{Y}\tilde{Q}^T \quad (1)$$

where  $\tilde{Q}$  is an  $N \times M$  matrix of eigenvectors. The  $n \times N$  numbers of the matrix  $Z$  are then replaced with  $M(n + N)$  numbers, which were used to reconstruct an approximate matrix  $\tilde{Z}$ .

Numbering the eigenvalues from the largest to the lowest, a sequence of  $N$  uncorrelated factors was obtained, which provide an optimal decomposition of the total variance. The eigenvalues indicate the amount of the total variance associated with each factor, and the ratio is given by the corresponding eigenvalue  $\lambda_p$ :

$$\frac{\text{variance of the factor}}{\text{total variance}} = \frac{\lambda_p}{\sum_{p=1}^N \lambda_p} \quad (2)$$

This equation provided a numerical indication of the importance of the factor, expressed as a percentage [61].

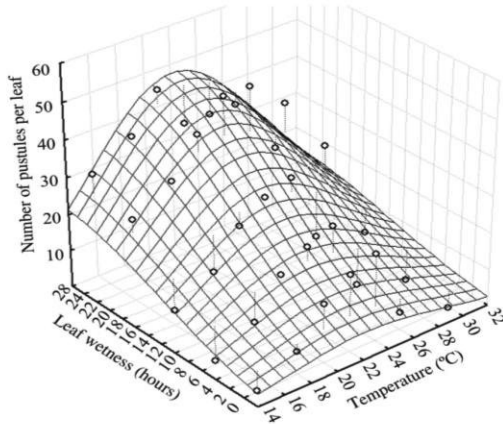
The first principal component obtained, which explains the major amount of the total variance, was adopted as an indicator of the intensity of cultivation of soybean, coffee and banana in Brazil. This component was subdivided in five classes of intensity within the municipal district boundaries using the natural breaks method [62].

### 3. Results and Discussion

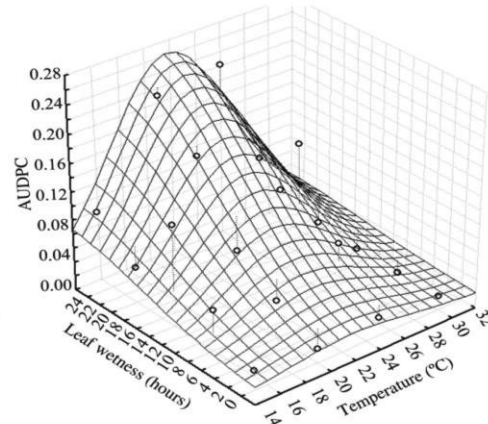
#### 3.1. Climate controls on the pathogens

The temperature and leaf wetness requirements of the pathogens coffee rust, soybean rust and black Sigatoka were obtained from non-linear regression models shown in Fig. 2. Based on the high R-squared values (over 0.75 in all cases), the models adequately represent the effects of temperature (T) and leaf wetness (M) on the diseases.

A 
$$NPL = (47.8618) \exp(-0.1546) \left( \frac{(M - 22.1701)}{(3.5696)} \right)^2 + \left( \frac{(T - 27.5366)}{(8.5501)} \right)^2 \right) R^2 = 0.75$$



B 
$$AUDPC = (0.2673) \exp(-0.01275) \left( \frac{(M - 21.8197)}{(0.7532)} \right)^2 + \left( \frac{(T - 28.3084)}{(2.1423)} \right)^2 \right) R^2 = 0.76$$



C 
$$AUDPC = (3.9217) \exp(-0.02238) \left( \frac{(M - 26.0041)}{(0.5348)} \right)^2 + \left( \frac{(T - 20.6027)}{(2.6421)} \right)^2 \right) R^2 = 0.85$$

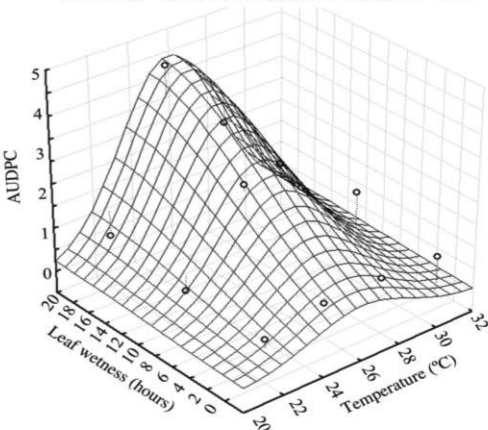


Fig. 2 Non-linear regression used to describe the effect of leaf wetness and mean air temperature in the severity of coffee leaf rust (A), soybean rust (B) and black Sigatoka (C). NPL = number of pustules per leaf; AUDPC = area under disease severity progress curve.

### 3.2. Spatial zoning of plant disease

For the purpose of zoning plant diseases in Brazil, annual average air temperature and rainfall were used as the source of variation of moisture content, which was used to estimate the moisture index. The moisture index was estimated for 1950–2000 and projected for 2020, 2050 and 2080 using high resolution mean annual air temperature and rainfall data for Minas Gerais using Alves and Carvalho's multiple regression model [57] (Fig. 3).

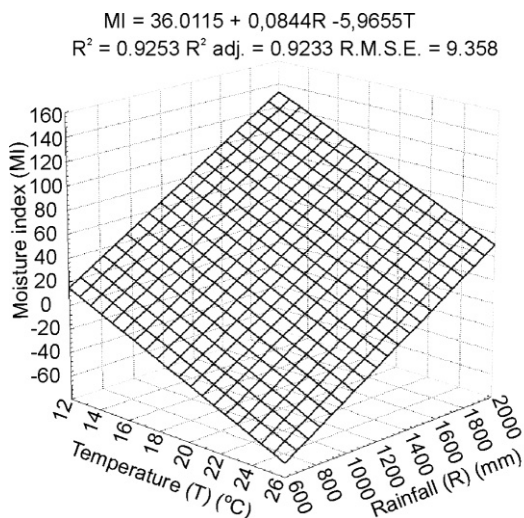


Fig. 3 Multiple linear regression model used to estimate the moisture index based on temperature and rainfall.

Subsequently, the leaf wetness duration was estimated for each scenario according to the nonlinear regression model developed for the city of Lavras, Minas Gerais, based on the relationship between moisture index and leaf wetness (Fig. 4).

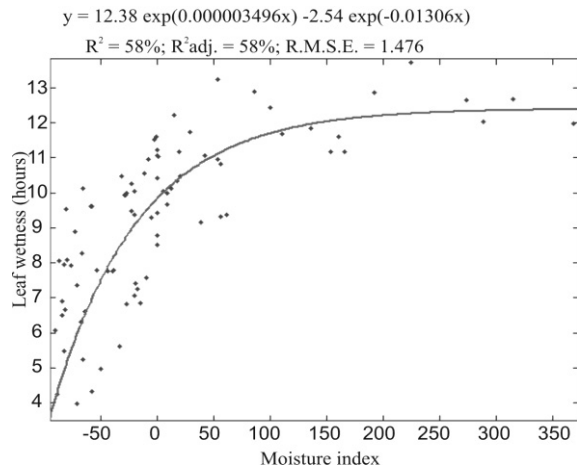


Fig. 4 Nonlinear regression used to estimate the average monthly leaf wetness depending on the moisture index.

The application of principal components technique enabled 57 variables to be grouped in the first principal component, explaining 87%, 88% and 90% of the data variability of the yield, harvest and cultivated areas of coffee, soybean and banana crops (Fig. 5).

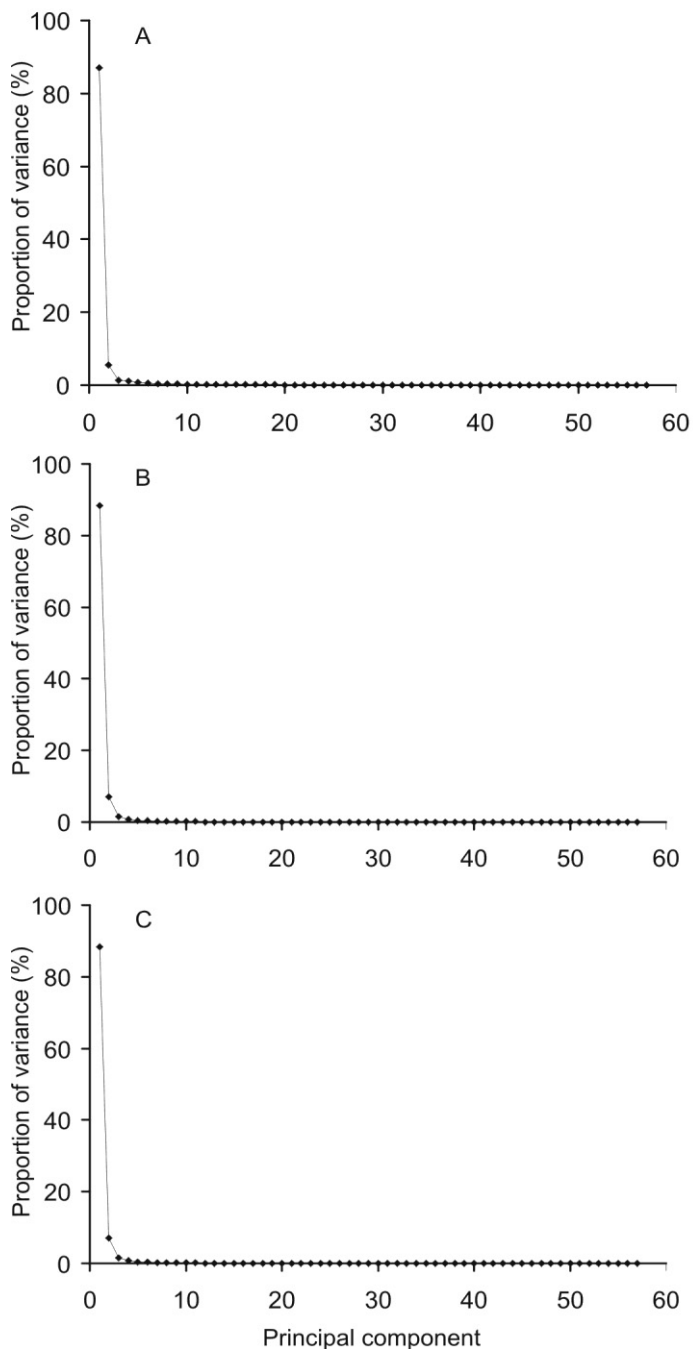


Fig. 5 The proportion of the explained variance in each of the 57 principal components for coffee (A), soybean (B) and banana (C).



The first principal component, representing information about crop intensity, was classified using the natural breaks technique for the 853 Brazilian municipal districts, characterizing the areas with higher crop intensity in Brazil (Fig. 6).

### 3.3. Effects of climate on plant disease

Applying the non-linear regression models shown in Fig. 2 to the input maps of temperature and leaf wetness generated the climatic zoning of coffee leaf rust (Fig. 7), soybean rust (Fig. 8) and banana black Sigatoka (Fig. 9) across Brazil. The areas of disease favorability were overlain to the major crop production regions to identify areas of very low, low, medium, high and very high favorability to epidemics (Fig. 7, 8 and 9).

As climate changes and warming increases, favorable areas for soybean and coffee rusts were projected to move toward the south of Brazil, particularly for the hottest scenario of 2080 (Fig. 7 and 8). Favorable areas for black Sigatoka move from the north to the central region of Brazil, representing a reduction in favorability to the disease in the 2080 scenario (Fig. 9).

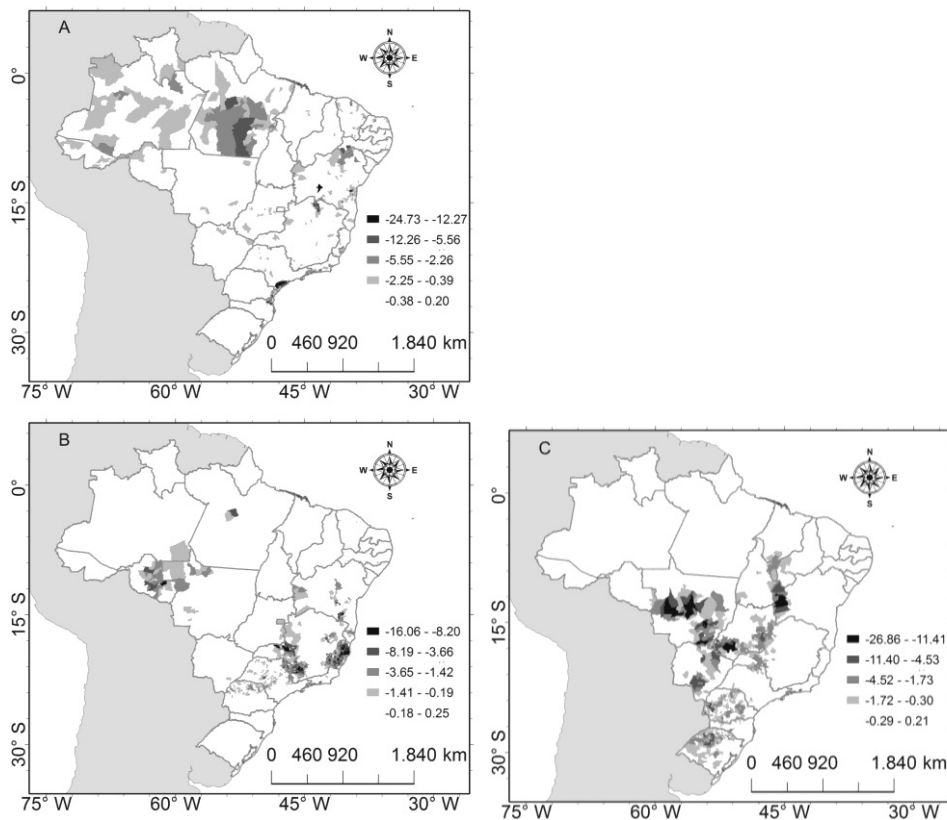


Fig. 6 Coffee (A), soybean (B) and banana (C) crop intensity in Brazil, based on the response of the first principal component derived from data on yield, harvest and cultivated areas for the years 1990 to 2008.

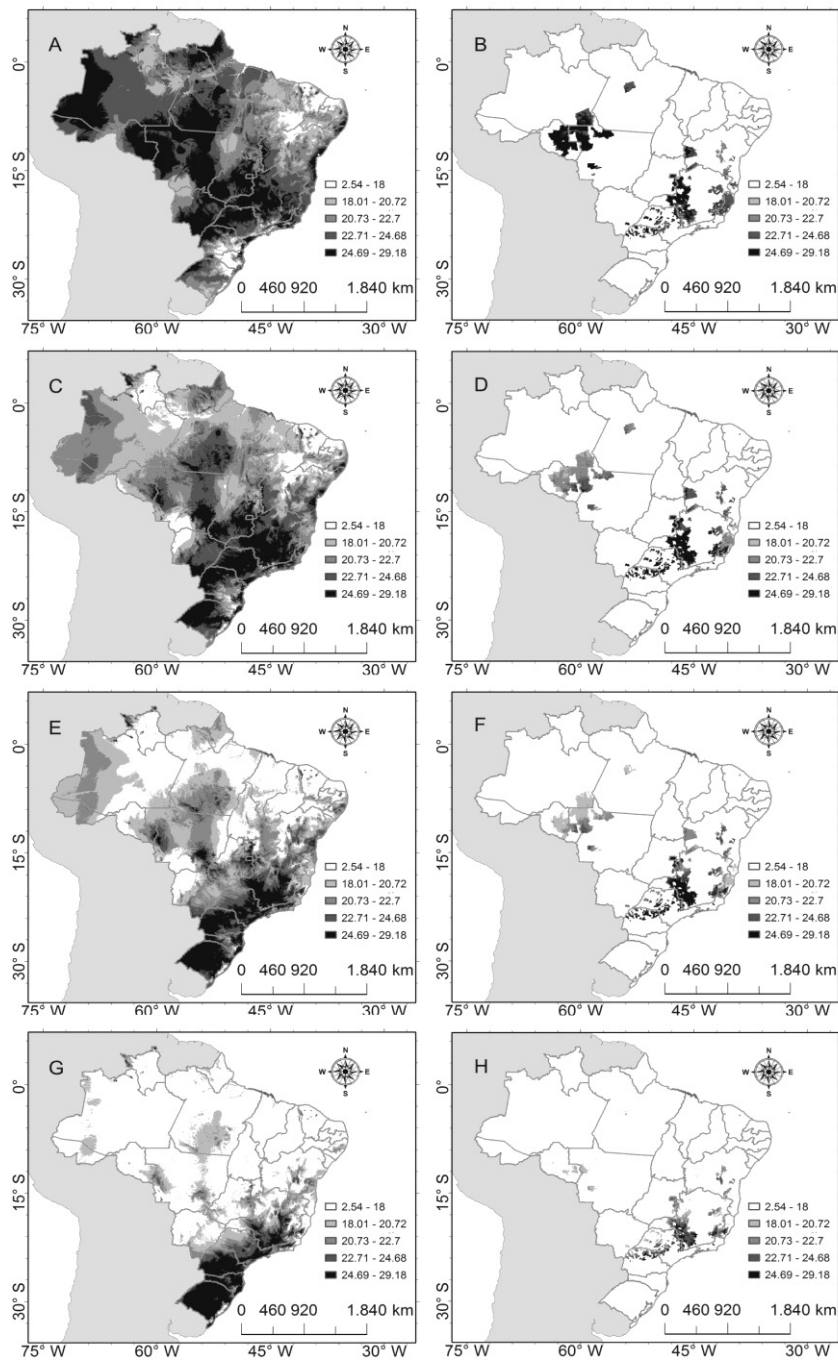


Fig. 7 Ecological zoning of coffee rust in Brazil (A, C, E, G) and in the main producing municipalities (B, D, F, H), for the periods 1950-2000 (A, B), 2020 (C, D), 2050 (E, F) and 2080 (G, H).

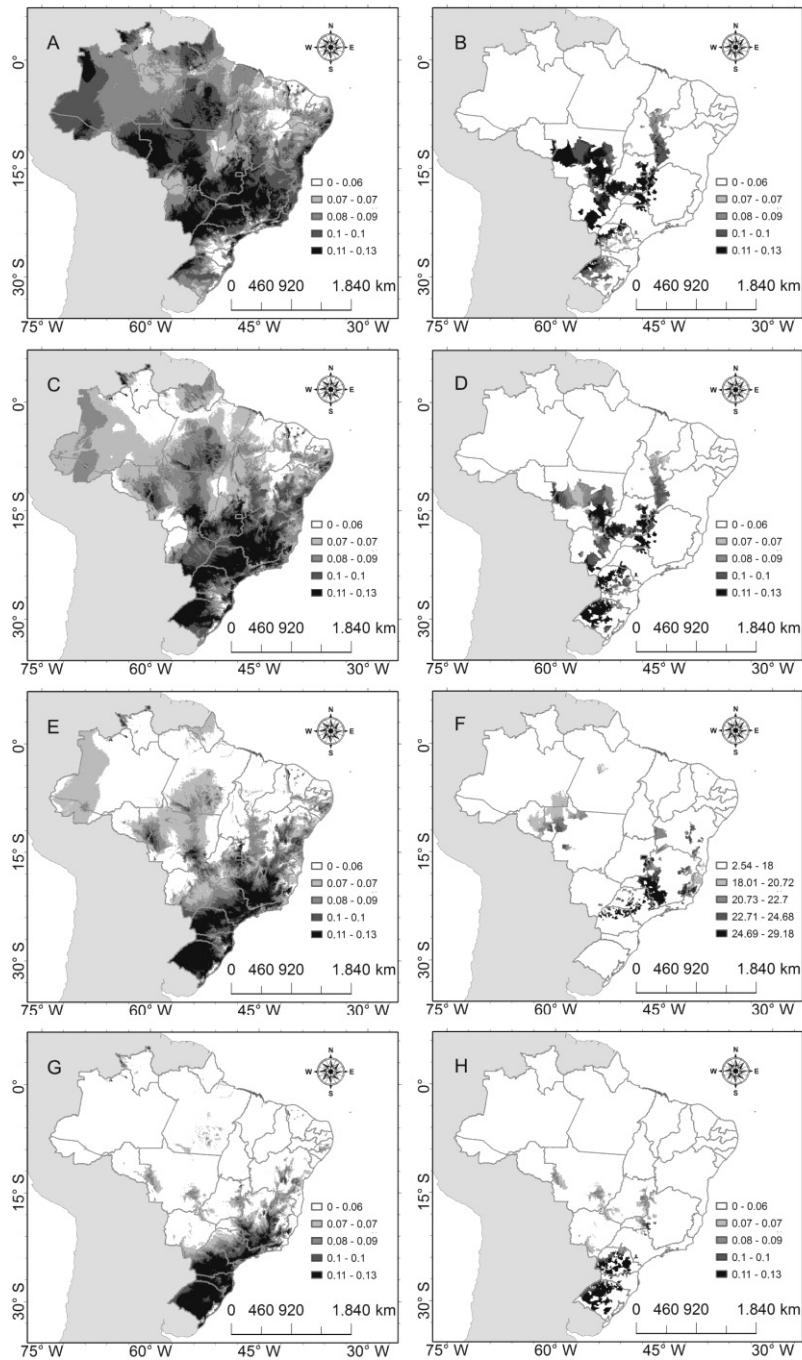


Fig. 8 Ecological zoning of soybean rust in Brazil (A, C, E, G) and in the main producing municipalities (B, D, F, H), for the periods 1950-2000 (A, B), 2020 (C, D), 2050 (E, F) and 2080 (G, H).

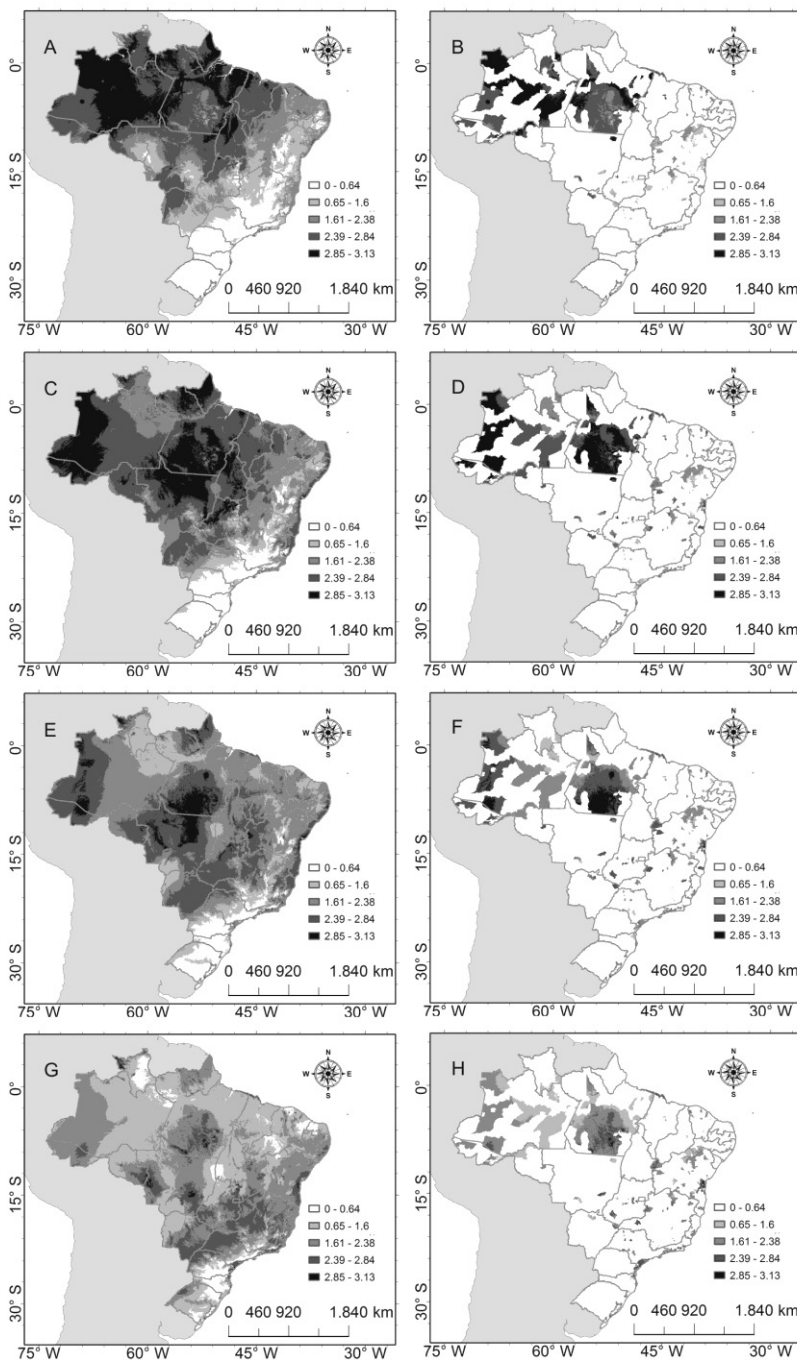


Fig. 9 Ecologically zoning of banana black Sigatoka in Brazil (A, C, E, G) and in the main producing municipalities (B, D, F, H), for the periods 1950-2000 (A, B), 2020 (C, D), 2050 (E, F) and 2080 (G, H).

#### 4. Conclusions

The areas that are potentially favorable to coffee, soybean and banana diseases in Brazil have been estimated according to the spatial-temporal variability of climatic variables and the geographical distribution of hosts.

The applied methodology enabled the visualization of the variation of areas favorable to epidemics under future scenarios of climate change.

The geoscientific and statistical modeling techniques developed in this study enabled the development of predictive models and the characterization of risk areas for soybean rust, coffee rust and black Sigatoka disease of banana. Furthermore, this study demonstrates the possibility of assessing the potential effects of global climate change in terms of the potential spatio-temporal progression of these epidemics in the future.

The results of the simulation of extreme levels of climate change presented in this work indicate that society will have to become more organized, in the context of the increase in social complexity, changed patterns of economic behavior, and the need for environmental preservation, in order to meet the demand for land resources that are influenced directly or indirectly by climate. In this context, the methodology presented in this study can contribute as a basis for adequate decision-making to minimize the risks and negative impacts of important diseases of soybean, coffee and banana agroecosystems in Brazil.

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