Climatic Risk Zoning for Potential Occurrence of Cacao Moniliasis Disease in Northeastern Brazil Under The Influence of ENSO Phases

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Research Article

Keywords: Theobroma cacao, Moniliophthora roreri, climate favorability, El Niño Southern Oscillation

Posted Date: June 29th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-639377/v1

Abstract

Air temperature and relative humidity are the main drivers of many fungal diseases, such as moniliasis (*Moniliophthora roreri*), which affects cocoa production worldwide. This disease occurs in some Latin American countries; however, it has not yet occurred in Brazil. Moniliasis could cause serious damage to the Brazilian cocoa production if present in the country. Therefore, to know the risks of moniliasis to cocoa production in the largest Brazilian producing region, in the state of Bahia, this study investigated the climatic favorability for the occurrence of this disease in this state, by defining and mapping the climatic risks and by assessing the influence of El Niño Southern Oscillation (ENSO) phases on it. Daily air temperature and relative humidity data from 28 weather stations of the national weather network in the state of Bahia, between 1988 and 2018, were employed to determine the risk index for cocoa moniliasis occurrence (RICM), based on the number of days favorable to the disease, which was categorized in five levels of favorability, ranging from "unfavorable" to "very favorable". Seasonal and annual RICM maps were generated by a multiple linear regression procedure, considering raster layers of latitude, longitude, and altitude. The maps showed a high spatial and temporal RICM variability in the state of Bahia, with the highest risk for moniliasis occurrence in the eastern part of the state, where most producing areas are located. The ENSO phase showed to influence cocoa moniliasis occurrence, with the years with a transition between El Niño and Neutral phases being the most critical for this disease in majority of assessed locations. These results show that cocoa producers in the state of Bahia, Brazil, should be concerned with moniliasis occurrence as a potential disease for their crops, mainly in the traditional producing regions and when ENOS is in a transition from El Niño to Neutral.

Introduction

The cocoa tree (*Theobroma* cacao) is indigenous to the Americas and is currently cultivated in about 119 tropical countries. It has great economic importance globally once it is the raw material for chocolate production. Brazil is currently the world's seventh cocoa producer, with 255,000 tons produced in a planted area of 685,000 ha (IBGE 2019). The state of Bahia stands out as the largest cocoa producer in Brazil, both in terms the planted area (480,000 ha) and in production (122.5 tons) (IBGE 2019).

Until the end of the 1980s, cocoa cultivation was the main agricultural activity in Bahia, mainly on the southern coast of the state. In the 1990s, production decreased substantially mainly due to the fungal disease known as "witch's broom", caused by *Moniliophthora perniciosa*. Another important fungal disease for cocoa crop is moniliasis, caused by *Moniliophthora roreri*, which affects fruit development and can drastically reduce cacao yield (Leach et al., 2002). High temperatures, around 25°C, and relative humidity above 85% comprise the optimal environmental conditions for moniliasis dissemination and infection in cocoa fruits (Moraes et al. 2012).

Cocoa moniliasis occurs in almost all cocoa-producing countries in Latin America, except Brazil, where the fungus *M. roreri* is still absent. Serious moniliasis outbreaks have led to termination of cocoa cultivation in large areas of Peru, Costa Rica, Colombia, and Mexico (Phillips-Mora and Wilkinson 2007). Several factors have contributed to the non-occurrence of this disease in the Brazilian cocoa areas, despite their favorable weather conditions for the fungus development. Plant quarantine and borders monitoring are the main measures for imposing restrictions on the movement of disease-infested plants or plant materials from one country to another (Karuppuchamy and Venugopal 2016).

Cacao cultivation in Brazil, especially in Bahia, is recovering from the major production breakdown caused by "witch's broom" in the 1990s and the occurrence of a new disease could be disastrous for farmers, once moniliasis has a high potential of damage (Ploetz 2016). Spores of *M. roreri* in contact with healthy fruits can cause initial infections without symptoms and persist for up to three months when there is a rapid progression of necrosis. Spores produced on necrotic fruits spread quickly by wind and rain, infecting other fruits. Remaining spores in the field can start another epidemic when a new crop cycle begins (Bailey et al. 2018).

Therefore, climatic risk zoning of moniliasis occurrence becomes an important and useful tool for crop planning and establishing strategic measures to minimize impacts on cocoa plantations. Risk zoning is based on the relationship between host susceptibility, pathogen aggressiveness, and environment conditions, which are factors that favor epidemic occurrence (Bailey et al. 2018).

The climatic risk for the occurrence of plant diseases has been studied for several pathosystems, such as common corn rust (Ferreira and Miranda 2020), stem canker in sunflower (Hulke et al. 2019), eucalyptus rust (Alvares at al., 2016; Nóia Júnior et al. 2018), sugarcane rust (Sentelhas et al. 2016), grape downy mildew, wheat rust and barley rust (Launay et al. 2014), citrus post-bloom fruit drop (Soares-Colletti et al. 2015), coffee leaf rust (Hinnah et al., 2020), and soybean rust (Del Ponte et al. 2011). From the best of our knowledge, studies on climatic risk for the occurrence of fungal diseases in cocoa are still scarce.

Air temperature, relative humidity, and rainfall are the main environmental drivers for determining the risks for plant diseases (Aparecido and Rolim 2020; Beruski et al. 2019). However, these factors present a high seasonal and interannual variability, imposing different risk levels for diseases occurrence. Climate variability is caused by fluctuations in atmospheric conditions, strongly related to the El Niño Southern Oscillation (ENSO) phenomenon. The ENSO is an oscillation of the ocean-atmosphere system in the equatorial Pacific with huge influences on weather conditions worldwide. The ENSO phases cause changes in temperature and rainfall patterns in different Brazilian regions, depending on their phase, El Niño (warm), Neutral, or La Niña (cold) (Nóia Júnior and Sentelhas 2019). On average, El Niño promotes less rainfall in Northeastern Brazil, whereas La Niña displays the opposite consequences, which may increase the risks for occurrence of fungal diseases (Hinnah et al., 2020).

Considering the influence of ENSO on climate variability, it is important to understand how its phases impact the risk of occurrence of fungal diseases. Different methodologies for risk zoning and assessment of the influence of ENSO on the occurrence of diseases are applied for different crops. Hinnah et al. (2020) mapped the risk of coffee rust by estimating the infection rate, based on disease progress curves. The ENSO influence was determined by Two-One-Sided-Tests (TOST), using confidence intervals, seeking to identify evidence of the influence of the difference between El Niño (EN) and La Niña (LN), not considering the transition phases. Sentelhas et al. (2016) considered the averages of sugarcane orange rust severity in each ENOS phase to identify how they influence the development of the disease. In such study, Sentelhas et al. (2016) estimated the disease severity and calculated an agroclimatic favorability index, using empirical weighting factors.

As plant diseases are highly influenced by environmental conditions, the development of tools based on weather information to assess the risk of diseases occurrence or damage are important to assist growers, consultants, and policy makers on defining strategies to optimize the control. The hypothesis of this study is that the risk of occurrence of cocoa moniliasis in the state of Bahia, Brazil, is variable in time and space as a consequence of climate variability, which in turn is influenced by the different phases of ENSO. Therefore, the aim of our study was to investigate the climatic favorability for the occurrence of moniliasis disease in cocoa crops and map the risks for this disease in the state of Bahia, Brazil, considering monthly and annual time scales, as well the influence of ENSO phases on disease favorability.

Materials And Methods

Study site

The study was conducted for the state of Bahia, due to its importance to cocoa production in Brazil, since it is the largest producer in the country. Bahia is one of the nine states in Northeastern region of Brazil, covering an area of 564.733 km². The state has large climate variability according to Köppen classification (Alvares et al. 2013), with humid tropical and semi-arid climates predominating in the state. Twenty-eight sites in the state of Bahia were considered in the present study, which represent those where weather stations were available, with 60.7% of them in a humid tropical zone (As, Af, Aw), 28.6% in a semi-arid zone (Bsh), and 10.7% in a humid subtropical zone (Cwb, Cw, and Cfa) (Fig. 1 and Table 1).

Table 1
Location, geographical coordinates (Latitude - Lat and Longitude - Lon), altitude (Alt), annual maximum (Tmax), average (Tavg) and minimum (Tmin) temperatures, annual average relative humidity (RHavg), annual rainfall, and Köppen´s climate classification for each location in the state of Bahia, Brazil.

Weather Station ID	Lat	Lon	Alt	Tmax	Tavg	Tmin	RHavg	Annual rainfall	Köppen classification
	(Degrees)		(m)	(°C)			(%)	(mm)	
1	-13.35	-40.11	755.61	26.7	20.8	17.1	71.1	816.2	As
2	-12.51	-40.28	249.89	31.4	24.8	18.9	67.9	617.9	BSh
3	-11.3	-41.86	747.16	30.2	23.5	17.5	57.6	609.0	BSh
4	-16.73	-39.54	194.67	29.4	23.9	20.0	77.1	1096.5	Af
5	-12.18	-38.96	230.68	30.0	24.4	20.3	73.0	754.3	As
6	-10.46	-40.18	558.24	29.7	24.2	19.9	59.6	752.3	As
7	-13.01	-38.53	51.41	29.0	25.6	22.9	78.1	1871.1	Af
8	-9.63	-42.1	400.51	31.8	26.7	22.4	56.1	621.4	BSh
9	-9.36	-38.21	252.69	32.2	26.2	21.7	60.7	513.0	BSh
10	-11.21	-41.21	1003.27	26.1	20.5	16.9	61.5	654.5	BSh
11	-10.43	-39.29	464.6	30.5	24.4	19.5	60.9	603.1	BSh
12	-12.56	-41.38	438.74	29.4	23.9	20.0	67.4	1068.7	Cwb
13	-11.18	-40.46	484.74	29.9	24.4	20.3	63.7	786.6	Aw
14	-13.81	-41.3	531.43	30.2	24.3	19.4	65.7	617.9	BSh
15	-12.66	-39.08	225.87	29.1	24.0	20.5	73.0	1117.4	Af
16	-13.33	-44.61	549.47	31.6	24.4	18.3	58.2	923.9	Aw
17	-11.08	-38.51	145.31	32.1	25.6	20.9	67.1	554.4	As
18	-14.28	-43.76	450.18	32.4	25.6	19.5	55.1	757.6	As
19	-17.73	-39.25	2.88	28.6	24.7	21.1	79.0	1405.3	Af
20	-15.66	-38.95	3.87	28.6	24.8	20.9	78.6	1591.8	Af
21	-14.06	-42.48	882.47	27.6	22.1	17.5	59.6	769.5	Cwc

The numbers in the column Weather Satation ID represent the following locations in the state of Bahia: 1 = Itiruçu; 2 = Itaberaba; 3 = Irecê; 4 = Guaratinga; 5 = Feira de Santana; 6 = Senhor do Bonfim; 7 = Salvador; 8 = Remanso; 9 = Paulo Afonso; 10 = Morro do Chapéu; 11 = Monte Santo; 12 = Lençóis; 13 = Jacobina; 14 = Ituaçu; 15 = Cruz das Almas; 16 = Correntina; 17 = Cipó; 18 = Carinhanha; 19 = Caravelas; 20 = Canavieiras; 21 = Caetité; 22 = Bom Jesus da Lapa; 23 = Barreiras; 24 = Barra; 25 = Alagoinhas; 26 = Serrinha; 27 = Santa Rita de Cássia; and 28 = Vitória da Conquista.

Weather Station ID	Lat (Degrees)	Lon	Alt (m)	Tmax (°C)	Tavg	Tmin	RHavg (%)	Annual rainfall (mm)	Köppen classification
22	-13.26	-43.41	439.96	32.8	26.0	20.0	53.7	797.5	As
23	-12.15	-45.00	439.29	32.7	25.2	19.2	57.7	1003.4	Aw
24	-11.08	-43.16	401.58	33.3	26.5	20.1	53.3	670.4	BSh
25	-12.14	-38.42	130.92	30.4	24.5	20.1	75.7	1073.3	Af
26	-11.63	-38.96	359.63	30.5	24.3	20.2	70.1	774.3	As
27	-11.01	-44.51	450.3	32.9	25.4	18.7	56.4	976.4	Aw
28	-14.88	-40.79	874.81	26.2	20.5	16.4	69.2	758.1	Cfa

The numbers in the column Weather Satation ID represent the following locations in the state of Bahia: 1 = Itiruçu; 2 = Itaberaba; 3 = Irecê; 4 = Guaratinga; 5 = Feira de Santana; 6 = Senhor do Bonfim; 7 = Salvador; 8 = Remanso; 9 = Paulo Afonso; 10 = Morro do Chapéu; 11 = Monte Santo; 12 = Lençóis; 13 = Jacobina; 14 = Ituaçu; 15 = Cruz das Almas; 16 = Correntina; 17 = Cipó; 18 = Carinhanha; 19 = Caravelas; 20 = Canavieiras; 21 = Caetité; 22 = Bom Jesus da Lapa; 23 = Barreiras; 24 = Barra; 25 = Alagoinhas; 26 = Serrinha; 27 = Santa Rita de Cássia; and 28 = Vitória da Conquista.

Weather data

Daily data on mean air temperature (T) and relative humidity (RH) were obtained from 28 weather stations from National Institute for Meteorology (INMET, https://bdmep.inmet.gov.br/) spread in the state of Bahia, aiming to determine favorable days for cocoa moniliasis occurrence for the period from 01/01/1988 to 31/12/2018, totaling 31 years (Table 1). Gaps in the weather series from INMET were filled with gridded data from the NASA POWER system (National Aeronautics and Space Administration Prediction of Worldwide Energy Resources), available at https://power.larc.nasa.gov/. This system provides daily weather data with a spatial resolution of 0.5° × 0.5º (Stackhouse et al. 2017). To ensure the suitability of NASA POWER data to fill the gaps in the INMET air temperature and relative humidity data base, we conducted an analysis of correlation between data from these two sources (Fig. S1 - Supplementary material). Also, the Pettit test for change-point detection (Pettitt, 1979) was conducted to verify the homogeneity of the weather data series (Verstraeten et al., 2006). The results of this analyses are presented in Table S2 in the Supplementary Material.

Climate Favorability of Cocoa Moniliasis

The favorable days for cocoa moniliasis occurrence (FCMO) along the year were determined according to air temperature (T) and relative humidity (RH) criteria proposed by Moraes et al. (2012) (Table 2). The daily favorability scores for T and RH, ranged from 0 (low favorability) to 3 (high favorability), as presented in Table 2: T < 18°C or T > 30°C, score 0; 18°C ≤ T ≤ 22°C, score 1; 26°C ≤ T ≤ 30°C, score 2;

22°C < T ≤ 26°C, score 3; UR < 70%, score 0; 70% ≤ UR ≤ 80%, score 1; 80% < UR ≤ 85%, score 2; UR > 85%, score 3.

Table 2
General, average air temperature (T) and relative humidity (RH) scores for classifying cocoa moniliasis favorability conditions. General score is the product between T and RH scores.

Adapted from Moraes et al. (2012).

General score	Favorability	T score	T (°C)	RH Score	RH (%)
9	Highly Favorable	3	22 < T ≤ 26	3	UR > 85
2 a 6	Favorable	2	26 ≤ T ≤ 30	2	80 < UR ≤ 85
1	Relatively Favorable	1	18 ≤ T ≤ 22	1	70 ≤ UR ≤ 80
0	Unfavorable	0	T < 18 or T > 30	0	UR < 70

After classifying each day for disease favorability, the scores for T and RH were multiplied to obtain the general daily score, reflecting the overall favorability condition, as follows: 9 – Highly Favorable (HF); between 2 and 6 – Favorable (F); 1 – Relatively Favorable (RF); and 0 – Unfavorable (UNF). After obtaining the total days of each favorability level (Table 2), the summation of days of RF, F and HF was computed, and the percentage of the days was performed in each year to evaluate the range in all locations and to determine the percentage range of favorable days to the occurrence of cocoa moniliasis (FCMO %), as follows:

$$FCMO\% = \left[{}^{(\#RF + \#F + \#HF)}/_{DOY}\right] \times 100$$

where: #RF, #F and #HF are, respectively, the number of days during the year under relatively favorable, favorable, and highly favorable conditions to moniliasis; and DOY is the number of days of the year (365 or 366).

Modeling Risk Index of cocoa moniliasis occurrence (RICM) in Bahia state

After determining daily favorability classes, the Risk Index of Cocoa Moniliasis occurrence (RICM) was calculated for monthly and annual scales for all years of the weather data series. The RICM was obtained by weighing each climate favorability class for cocoa moniliasis through arbitrary weights algebra (Paule and Mandel, 1982), according to the following equation:

$$\text{RICM}\ (\%) = \frac{(1 \times \#\text{UNF} + 2 \times \#\text{RF} + 3 \times \#\text{F} + 4 \times \#\text{HF})}{\text{ND}} \times 100$$

where: # is the total number of days in the month or year, during the historical, series with the different classes for cocoa moniliasis favorability (UNF = unfavorable; RF = relatively favorable; F = favorable; HF = highly favorable); ND is the total number of days of the year or month. This approach was recently used by Sentelhas et al. (2016) for sugarcane orange rust and by Soares-Colletti et al. (2016) for post bloom drop in citrus.

Mapping RICM

After calculating the RICM for the 28 weather stations (Table 1; Fig. S2), multiple linear regression (MLR) models were developed to estimate this variable based on geographical coordinates (latitude - Lat; longitude – Lon) and altitude (Alt) (Table 1), as also employed by other authors (Evrendilek and Ertekin, 2007; Yamada and Sentelhas, 2011; Alvares et al., 2013; Monteiro and Sentelhas, 2014; Sentelhas et al., 2016; Soares-Colletti et al., 2016; Souza et al., 2021). This procedure allows to spatialize the results of the multiple regression models, considering the total of pixels present in the state of Bahia, Brazil.

The Stepwise Regression Procedure was used to choose the best model for each condition (months and year) through the forward selection of predictor variables, based on a significant p-value ($p < 0.05$) (Wilkinson, 1979). The analysis was performed in the *olsrr* package (Aravind, 2018) of the R software (R Core Team 2019). The models were calibrated with 70% of the total database (stations 10 to 28) and tests or validations were performed with the remaining 30% (stations 1 to 9). The performance of the multiple linear regression models was assessed by the following errors and indices: mean absolute error (MAE); mean error (ME) (Urquhart et al. 2013), coefficient of determination (R^2) (Miles, 2014); Willmott's index of agreement (d) (Wilmott, 1981); confidence index (c) (Camargo and Sentelhas, 1997), and coefficient of variation (CV) (Canchola et al. 2017).

A vector layer with a resolution of 1 x 1 km was obtained in the QGIS software (QGIS Development Team, 2019) from where Lat and Lon were extracted for each point, generating two different layers. Alt was obtained from the digital elevation model (DEM) of the Shuttle Radar Topography Mission - SRTM (https://www2.jpl.nasa.gov/srtm/) of the National Aeronautics and Space Administration - NASA (Rodriguez et al. 2005), with a 90 m resolution. DEM was resampled to match the resolution of the Lat and Lon layers (1 km^2). Lat, Lon, and Alt layers and the multiple linear regression (MLR) models were, therefore, the basis to develop RICM maps. The "Spatial Analyst Tools" in QGIS were used to estimate RICM by "Map Algebra", considering monthly and annual MLR models for the state of Bahia (Table A1, Supplementary Material). The procedure resulted in monthly and annual RICM raster layers. The steps and procedures to obtain the final RICM maps are presented in Fig. 2.

Influence of ENSO phases on cocoa moniliasis occurrence

The ENSO phases were classified for each year as El Niño (EN), La Niña (LN), and Neutral (N), according to the Climate Prediction Center of U.S. National Oceanic and Atmospheric Administration (NOAA, 2020), considering the period between 1988 and 2018. Pacific sea surface temperature (SST) anomaly in the position Niño 3.4 (5°N-5°S, 120°-170°W) was used as reference to determine the different ENSO phases. The Niño 3.4 region is the most closely used for detecting temperature changes associated with ENSO (Lyon and Barnston 2005; McPhaden et al. 2006). When SST anomaly is ≥ + 0.5°C above normal for 5 consecutive 3-month running averages the El Niño (EN) phase is assumed. When SST anomaly is ≤ -0.5°C below normal for 5 consecutive 3-month running averages, it is considered as a La Niña (LN) episode. Finally, when SST anomaly remains between + 0.5°C and − 0.5°C, the Neutral (N) condition is established. The years with the transition between two different ENSO phases were also considered, which means that along the year two different ENOS phases occurred. For the period assessed, only the transitions from El Niño to Neutral (EN/N) and from El Niño to La Niña (EN/LN) phases were observed. Afterward, the cumulative of favorable days (RF, F and HF) for cocoa moniliasis occurrence from 1988 to 2018 were computed for 28 locations assessed considering the different ENSO phases. Posteriorly, we performed the summation of favorable days for EN, LN, N, EN/N and EN/LN phases along the 31 years, according to Sentelhas et al. (2016). The percentage of favorable days for moniliasis occurrence as a function of the ENSO phases (FD_{ENSO}) was determined by dividing the sum of favorable days for cocoa moniliasis occurrence (FCMO) by the total days of the years in which each ENSO phase occurred, also considering the leap years, when necessary. In the entire historical series assessed (1988–2018), a total of 5, 9, 14, 1 and 2 years were classified as EN, LN, N and their transitions EN/LN and EN/N, respectively (Eq. 3).

$$FD_{ENSO} = \frac{\sum FCMO}{\Sigma ENSO\ days} \quad (3)$$

where: ΣFCMO is the total of favorable days for cocoa moniliasis occurrence and ΣENSO days is the total days of the years in which each ENSO phase occurred, also considering the leap years.

Results

Climatic favorability for cocoa moniliasis occurrence (FCMO%)

The average FCMO% and its variability of for each assessed location in the state of Bahia are presented in Fig. 3. The coastal region, represented by Guaratinga, Salvador, Caravelas, Canavieiras, and Alagoinhas (stations 4, 7, 19, 20, and 25, respectively), is the one with the highest average FCMO%, greater than 70% (Fig. 3a and 3c). In addition, it is possible to observe from Fig. 3b that three of these stations, located in the seashore (Slavador, Caravelas, and Canavieiras), have a highly stable FCMO%, which shows that the climate is less variable and always favorable for moniliasis occurrence. The regions represented by Itiruçu, Feira de Santana, Cruz das Almas, and Serrinha, (stations 1, 5, 15 and 26, respectively) presented average FCMO% between 50–60%, whereas the other regions, further west, had average FCMO% lower < 30%, but with a higher interannual variability than in the seashore (Fig. 3b and 3c). A non-parametric statistical analysis (Pettistt´s test) showed that FCMO% differ between regions ($p < 0.05$), as presented clearly in Fig. 3c, which is a function of spatial and interannual climate variability observed in the state, being ENSO the main responsible for the variability among years (Nóia Júnior and Sentelhas 2019), whereas differences in latitude, longitude, and altitude, are those responsible for the spatial climatic variability between the assessed locations.

Risk Index of cocoa moniliasis occurrence (RICM)

The RICM for each assessed location is shown in Fig. 4. The RICM was always greater than 30% for all assessed locations, except for Remanso (8), the northernmost assessed location. Other locations had RICM above 50%, following the same trend of FCMO%. Among the assessed locations with the highest percentages of favorable days to moniliasis occurrence are Alagoinhas, Canavieiras, Cruz das Almas, Salvador, Feira de Santana, Guaratinga, and Caravelas (stations, 25, 20, 15, 7, 5 and 4, respectively), all of them located in the eastern part of the state, near the coast. Among these locations Caravelas, the southernmost assessed location, was the one with the highest RICM, above 70%. The seasonal variation of RICM of each assessed location is presented in the Fig. S2 in the Supplementary material, in which a strong influence of the season of the year can be seen on the potential climatic risk for moniliasis occurrence of in the state of Bahia, with higher risks during the summer in the interior of the state, whereas on the coast the highest risks occur during the winter.

Climatic risk zoning for cocoa moniliasis occurrence

The development and validation of the annual and monthly models to estimate the risk for cocoa moniliasis occurrence (RICM) for the state of Bahia, Brazil, and their statistical performance are presented in Table S1 in the Supplementary material. The maps of climatic risk zoning for cocoa moniliasis occurrence (Fig. 5), on a monthly basis, are presented in Fig. 5a. High spatial and temporal RICM variability occurs in the state of Bahia. In general, in the western part of the state, with predominance of the Cerrado biome, the climatic risk for moniliasis occurrence in cacao plantations is low, always below 30% between May and October, and slightly above 50% from December to March.

In the eastern part of the state, close to the coast, mainly further south, the risk for cocoa moniliasis occurrence is always above 50%. In some months, it reaches more than 70%, showing high favorability for disease occurrence, especially from May to July and from October to December, when air temperature and humidity conditions are more favorable to moniliasis.

In the central and northern regions of the state, where predominates a semi-arid climate and biome (Almeida et al. 2017), there is a huge variability of the climatic risk for moniliasis occurrence over the months (Fig. 5). In the central portion of the state, the disease risk during the autumn-winter months is always below 50%. On the other hand, during the spring-summer months the risk for moniliasis becomes higher, following the increase of rainfall. In the northern part of the state, the disease risk is always below 50% throughout the year, remaining even lower in the winter months until the beginning of spring, when rainfall is extremely low.

The mean annual map of the climate risk zoning for moniliasis occurrence in cocoa crop is presented in Fig. 5b. This map, which considers the average conditions for moniliasis occurrence all year long, shows clearly that there are three zones of RICM in the state of Bahia. The most prevalent zone in the state covers great part of the northern, central, and western regions of the state, with RICM values below 50%. The second most prevalent area, with RICM above 50%, is located mainly on the coastal zone, stretching from the shore to about 100 km towards the interior of the state. The third zone is found in some high-altitude regions in the center and in the extreme northwest of the state of Bahia, where the climatic risk for moniliasis occurrence is below 30%.

El Niño Southern Oscillation influence on the risk for cocoa moniliasis occurrence in the state of Bahia

The influence of ENSO phases on the interannual variability of the total number of favorable days for the occurrence of cocoa moniliasis in the state of Bahia is presented in Fig. 6. The locations less influenced by different ENSO phases are those located close to the coast, represented by Salvador, Caravelas, and Canavieiras (station 7, 20 and 19, respectively), where no difference was observed for favorable days for moniliasis occurrence between EN, LN, N and their transitions. This is justified by the constant favorable weather conditions (T and RH) for moniliasis disease along the year and between years in these locations.

The assessed locations in the west, central and northern regions of the state, which normally have less rainfall during the year, which results in lower favorability for moniliasis occurrence, were those most influenced by the ENSO phases (Fig. 6 and Fig. S3). In these regions, the transition from EN to N showed to be the most favorable to the disease. However, this kind of condition occurred only during two years of the historical series, which makes this analysis preliminary and requiring more data to obtain conclusive results. In a similar condition, but in a opposite way, the transition from EN to LN showed to be the less favorable for moniliasis, but in this case also there is very few data to make any conclusion.

When considering the classical ENSO events (EN, LN, and N), the sites located in the west of the state presented higher favorability during EN and LN year than in the N years, which differed from the central and northern parts of the state where the number of days favorable to moniliasis along the year was higher during EN events, followed by LN and N years (Fig. 6 and Fig. S5).

Discussion

Our analyses allowed to identify a high temporal and spatial variability of climatic risk for occurrence of cacao moniliasis in the state of Bahia (Fig. 3 to Fig. 7), which is explained by the distinct climatic conditions of the different regions of the state (Medauar et al. 2020), as presented in Fig. 1.

The spatial climatic variations in the state of Bahia are due to the conjunction of different meteorological systems that affect the region, such as Intertropical Convergence Zone, Cyclonic Vortexes, Frontal Systems, South Atlantic Convergence Zone, sea/land breezes, and predominant winds. Additionally, another important aspect is the region relief, comprised of plains, valleys, highlands, mountains, which generate different climatic conditions.

The spatial distribution of climatic risk for moniliasis occurrence (Figs. 5 and 6) shows that, in general, the coastal region of the state of Bahia is the most favorable for disease development. However, the central and northern regions are less favorable, while the western region shows periods of high and low favorability, depending on the season of the year. The spring-summer months are rainy in most of the state, increasing the risk for disease occurrence, whereas autumn-winter months are dry (Medauar et al. 2020). The opposite situation is observed on the coastal region of the state, where the most favorable period for moniliasis occurrence is in the autumn-winter time, corresponding to the rainy season for this part of the state. The rainfall regimes in the state of Bahia regulate the main variables (temperature and relative humidity) that influence the developmental cycle of *M. roreri*.

In general, the climatic risk indices for moniliasis occurrence in the northern region of Bahia are always low throughout the year. This part of the state is composed of regions with climatic characteristics of the northeastern semiarid. The different atmospheric circulation systems in this region display complex climatology, reflecting in great climatic variability, mainly in relation to the rainfalls, which vary a lot in terms of amount, time, and space (Medauar et al. 2020). Thus, low average rainfall is poorly distributed throughout the year, making the conditions unfavorable for the development of cacao diseases, including moniliasis.

In the central portion of the state of Bahia, mountains and highlands generate an orographic effect, which causes more annual rainfall than in the semi-arid region (Dourado et al. 2013), resulting in a climatic risk for moniliasis occurrence a little higher than in the northern part of the state; however, still considered a medium risk when compared to the coastal region (Fig. 6).

In the western region of the state of Bahia, with a predominance of the Cerrado biome and well-defined rainy and dry seasons (Medauar et al. 2020), the climatic risk for moniliasis occurrence ranges from medium to low. In this region, as well as in the central and northern parts of the state of Bahia, risks are lower for moniliasis occurrence, which allows avoiding moniliasis occurrence on cocoa plantations (escape areas), along with the use of new cultivars and cropping technologies. Although these regions are not traditional for cocoa production in the state, they have the potential for expanding cocoa cultivation, mainly when irrigation is considered (Franco et al. 2019)

Commercial crops in escape areas could provide good development and low risk for cocoa production in Bahia. In case moniliasis pathogen occurs in the state, prolonged periods of drought and low relative humidity during the dry season of the year could hinder pathogen survival from one season to another, reducing disease proliferation from field to field (Bailey et al. 2018). However, as cocoa crops should be irrigated in these regions, the use of localized irrigation systems (dripping or micro-aspersion) should be preferred to avoid wetness on leaves and fruits. In addition, other techniques, such as picking infected fruits, pruning, and the use of disease-tolerant cultivars could also make cocoa cultivation viable in regions with low phytosanitary problems.

On the other hand, on the coastal region, especially further south, where the climate is more suitable for cocoa production (Franco et al. 2019), but also more favorable for cocoa moniliasis occurrence (Fig. 4), the adoption of disease-resistant varieties and the use of fungicides, once they prove their efficiency, are the main strategies to avoid serious damages to the cocoa production system in the event of moniliasis infecting this region. Otherwise, serious socioeconomic impacts may occur, since the coastal part of Bahia is currently the state's main cocoa producing region (IBGE, 2019).

The interannual variability of climatic conditions and its influence on favorability for cocoa moniliasis disease in the state of Bahia, Brazil, is mainly associated to the ENSO phenomenon (Figs. 3 and 6). The effects of ENSO phases on climatic conditions are highly variable in Brazil and in the northeastern region of the country, where altitude, topography, dynamics of currents, and air masses promote constant climatic variation, affecting the spatial and temporal distribution of the risk for diseases, in general (Nóia Júnior et al. 2018).

For the specific case of cocoa moniliasis, the influence of ENSO phases on this disease in the state of Bahia varied according to the region of the state and very few differences between these phases were observed (Fig. 6). These results are similar to what was observed by Hinnah et al. (2020) for coffee leaf rust (CLR) in the state of Bahia. Using the Two-One-Sided-Test (TOST), these authors found that there is no clear evidence of differences between the ENSO phases (El Niño x La Niña) impacts on such coffee disease.

The regions close to seashore were those with no influence of ENSO phase on disease risk, since they always have climatic conditions very favorable for moniliasis, independently of the ENSO phase. In the west of the state, no difference in the relative number of days favorable to moniliasis were found between EN and LN phases, which were higher than N. In the central and northern part of the state EN showed to favor moniliasis more than the other ENSO phases. For the transitions of phases, no conclusive results could be obtained, since these events only happened twice for EN/N and once for EN/LN. Despite of that, during the years with the transition from EN to N the percentage of days favorable to the disease was the highest, whereas for the transition from EN to LN such percentage was the lowest, in most of the assessed locations (Fig. 6).

Among the planning execution options for controlling moniliasis, in case it becomes present in Bahia, are the development of resistant varieties adapted to the different edaphoclimatic conditions of the state, maintenance of optimum plant nutrition, pruning schedule to keep the crop with a more airy microclimate, thus reducing the humidity and increasing the incidence of solar radiation inside the canopy, use of integrated cultivation systems and localized irrigation techniques to reduce the leaf wetting periods, in addition to a rational chemical management, as long as there are efficient products for the control of this disease.

Conclusions

The coastal region has the greatest potential for the occurrence of cocoa moniliasis in the state of Bahia, while in the northern, central and western regions, the risks are reduced, with an increase in the rainy season (spring-summer). In addition, it is possible to observe that the influence of ENSO phases on this disease in Bahia varies according to the region of the state and there are very few differences between these phases. The climatic risk maps for the occurrence of cocoa moniliasis in Bahia is a particularly useful tool for cocoa cultivation planning in the face of this new disease is still absent in the state. These risk maps allow to design rational strategies for adequate planning to combat and live with the arrival of the pathogen even before it settles in the region. Despite the importance of our findings, this study was done considering macroclimatic conditions, therefore, it is recommended to investigate more about the favorability conditions for moniliasis under topoclimatic and microclimatic scales.

Declarations

ACKNOWLEDGEMENTS -The authors express their gratitude to the anonymous reviewer who contributed expressively to the improvement of the final version of this manuscript.

AUTHOR CONTRIBUTION - Conceptualization: Galvão, I.M, Pereira, G.S., Sentelhas, P.C.; Methodology: Galvão, I.M, Pereira, G.S., Sentelhas, P.C.; Formal analysis and investigation: Galvão, I.M, Pereira, G.S., Sentelhas, P.C.; Writing - original draft preparation: Galvão, I.M, Pereira, G.S. Writing - review and editing: Galvão, I.M, Pereira, G.S.

FUNDING - This study was partially funded by Brazilian Research Council (CNPq) and by Coordination of Superior Level Staff Improvement (CAPES), both from the Brazilian Federal Government.

DATA AVAILABILITY

All the data used for this study are available and provided by the public entities (National Institute of Meteorology - INMET).

CODE AVAILABILITY - Not applicable.

Ethics approval - Not applicable.

Consent to participate - Not applicable.

Consent for publication - Not applicable.

Conflict of interest - The authors declare no competing interests.

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Figures

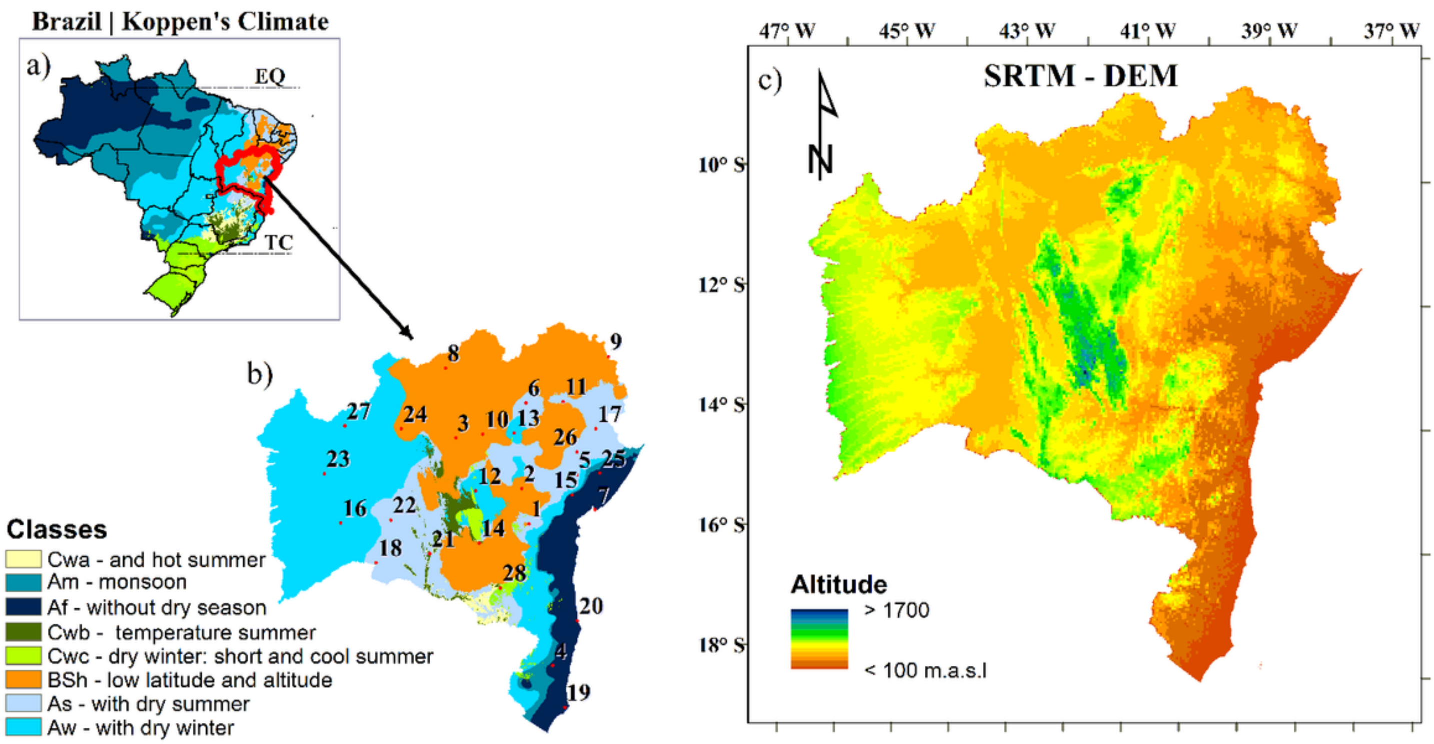

Figure 1

Köppen climate classification according to Alvares et al. (2013) for Brazil (a) and the state of Bahia (b), and digital elevation model (DEM) from SRTM (c). The classifications of Köppen climate system: tropical zone begins with letter A; semiarid zone with letter B; and humid subtropical zone with letter C. EQ = Equator line and TC = Tropic of Cancer. The numbers in b represent the weather stations located in: 1 = Itiruçú; 2 = Itaberaba; 3 = Irecê; 4 = Guaratinga; 5 = Feira de Santana; 6 = Senhor do Bonfim; 7 = Salvador; 8 = Remanso; 9 = Paulo Afonso; 10 = Morro do Chapéu; 11 = Monte Santo; 12 = Lençóis; 13 = Jacobina; 14 = Ituaçu; 15 = Cruz das Almas; 16 = Correntina; 17 = Cipó; 18 = Carinhanha; 19 = Caravelas; 20 = Canavieiras; 21 = Caetité; 22 = Bom Jesus da Lapa; 23 = Barreiras; 24 = Barra; 25 = Alagoinhas; 26 = Serrinha; 27 = Santa Rita de Cássia; and 28 = Vitória da Conquista. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

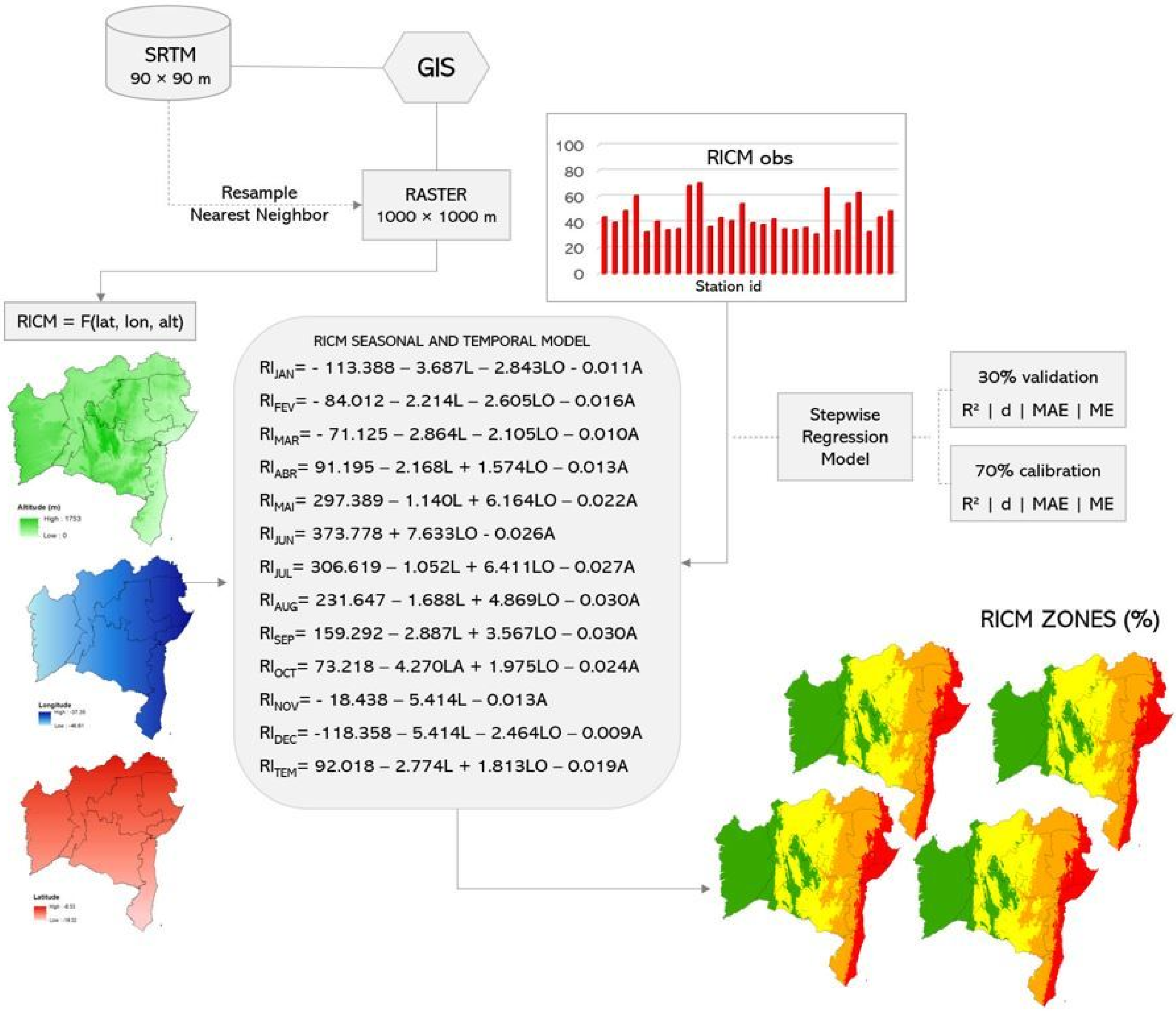

Figure 2

Procedures for modelling and mapping the climatic risk for cocoa moniliasis occurrence (RICM) in the state of Bahia. Alt or A = altitude, Lat or L = latitude and Lon or LO = longitude. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

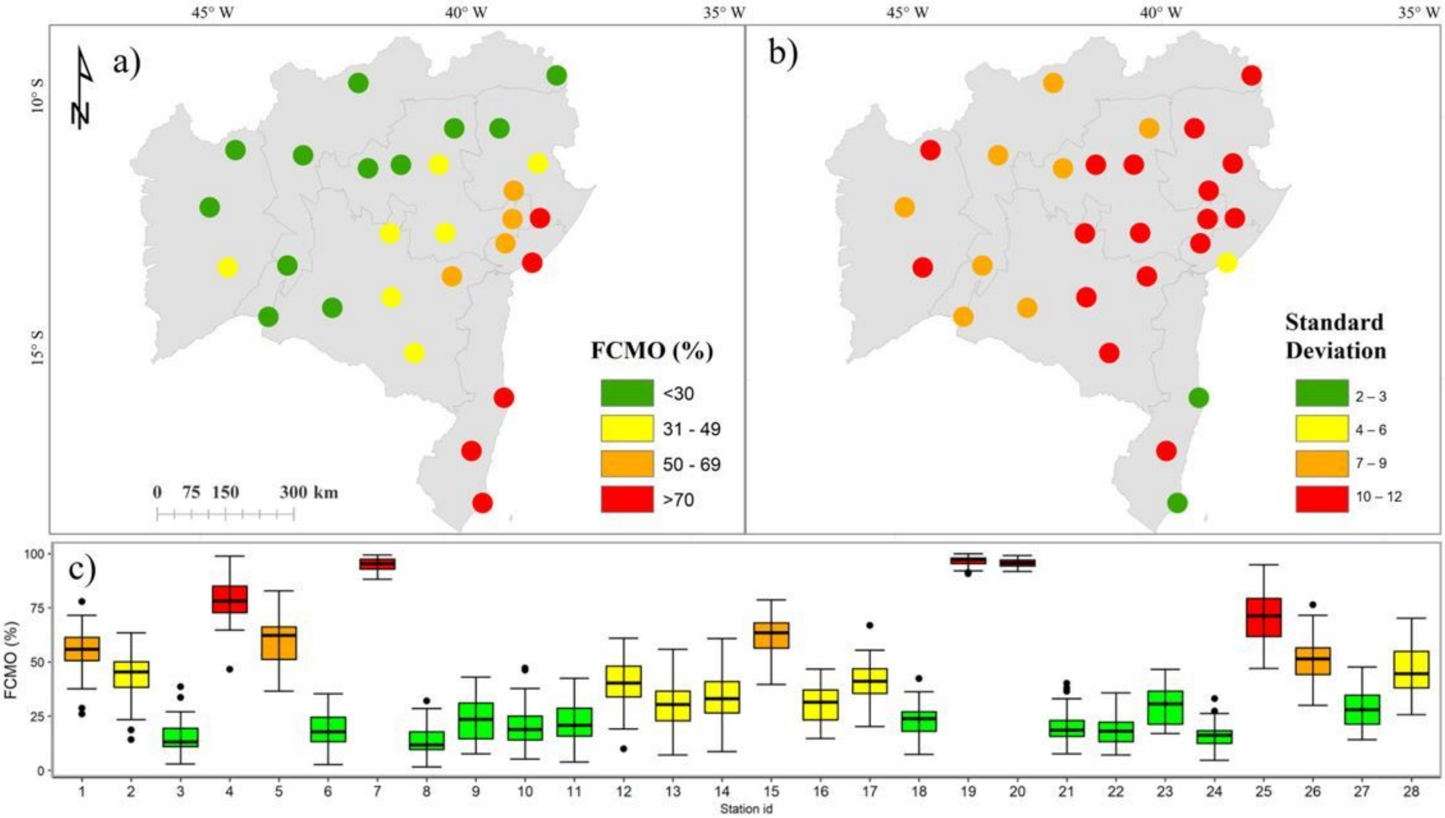

Figure 3

Average (a), standard deviation (b) and interannual variability for favorability of cocoa moniliasis occurrence (FCMO%) in 28 locations assessed in the state of Bahia, Brazil. The number in figure c are presented at Table 1 and Fig. 1 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

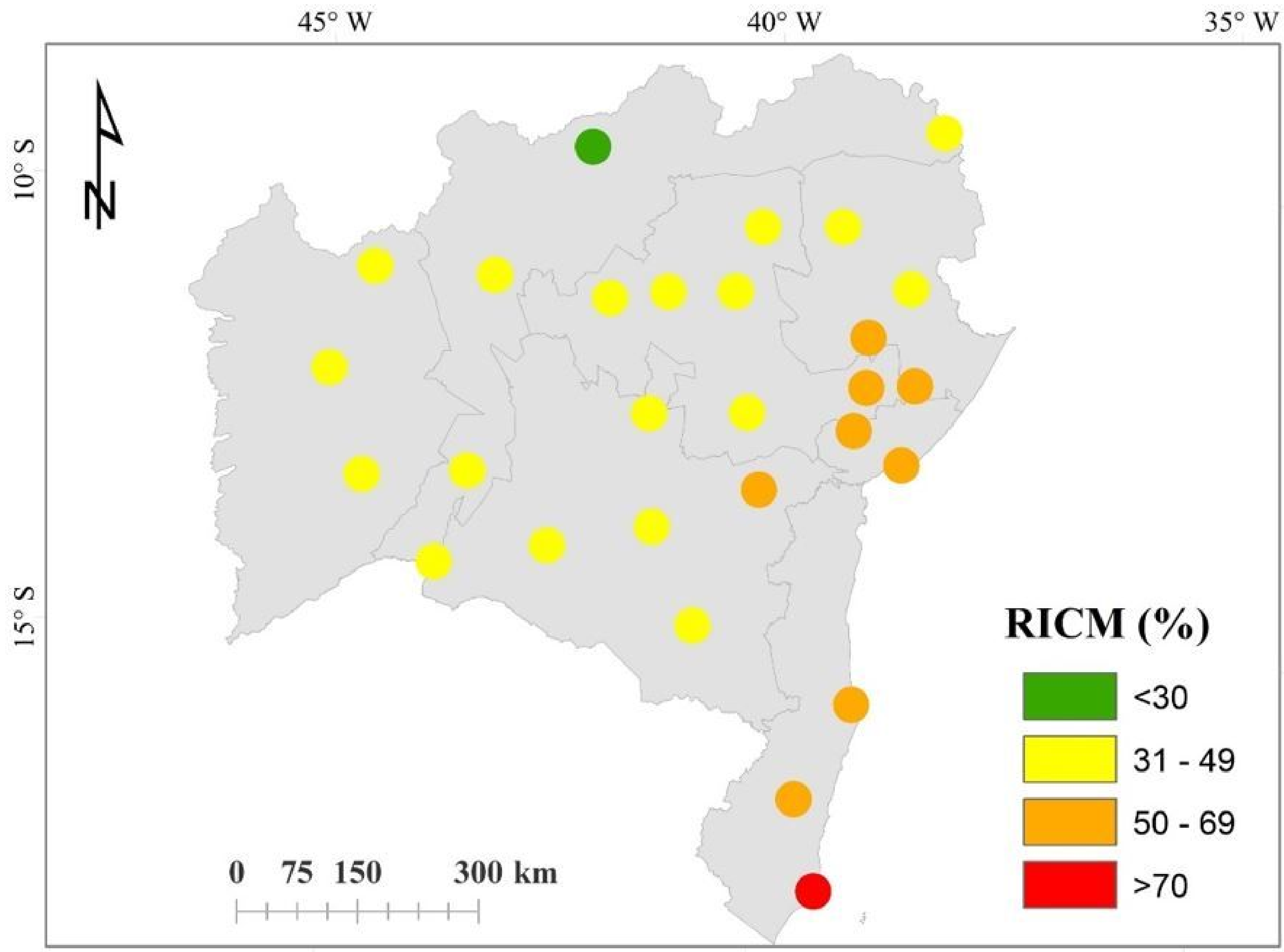

Figure 4

Climatic risk index of cocoa moniliasis occurrence (RICM) for 28 locations in the state of Bahia, Brazil
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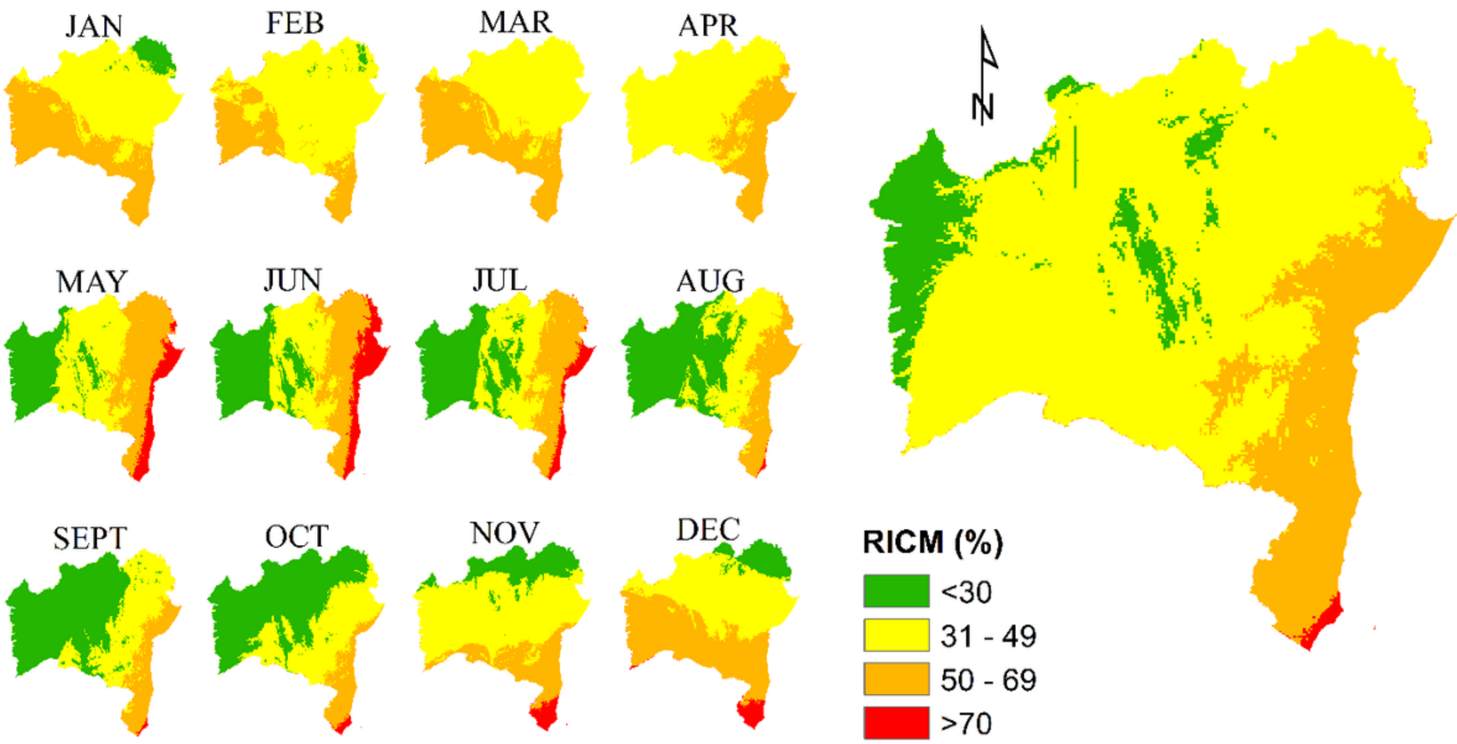

Figure 5

Monthly (a) and annual (b) climatic risk index of cocoa moniliasis occurrence (RICM) for the state of Bahia, Brazil. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

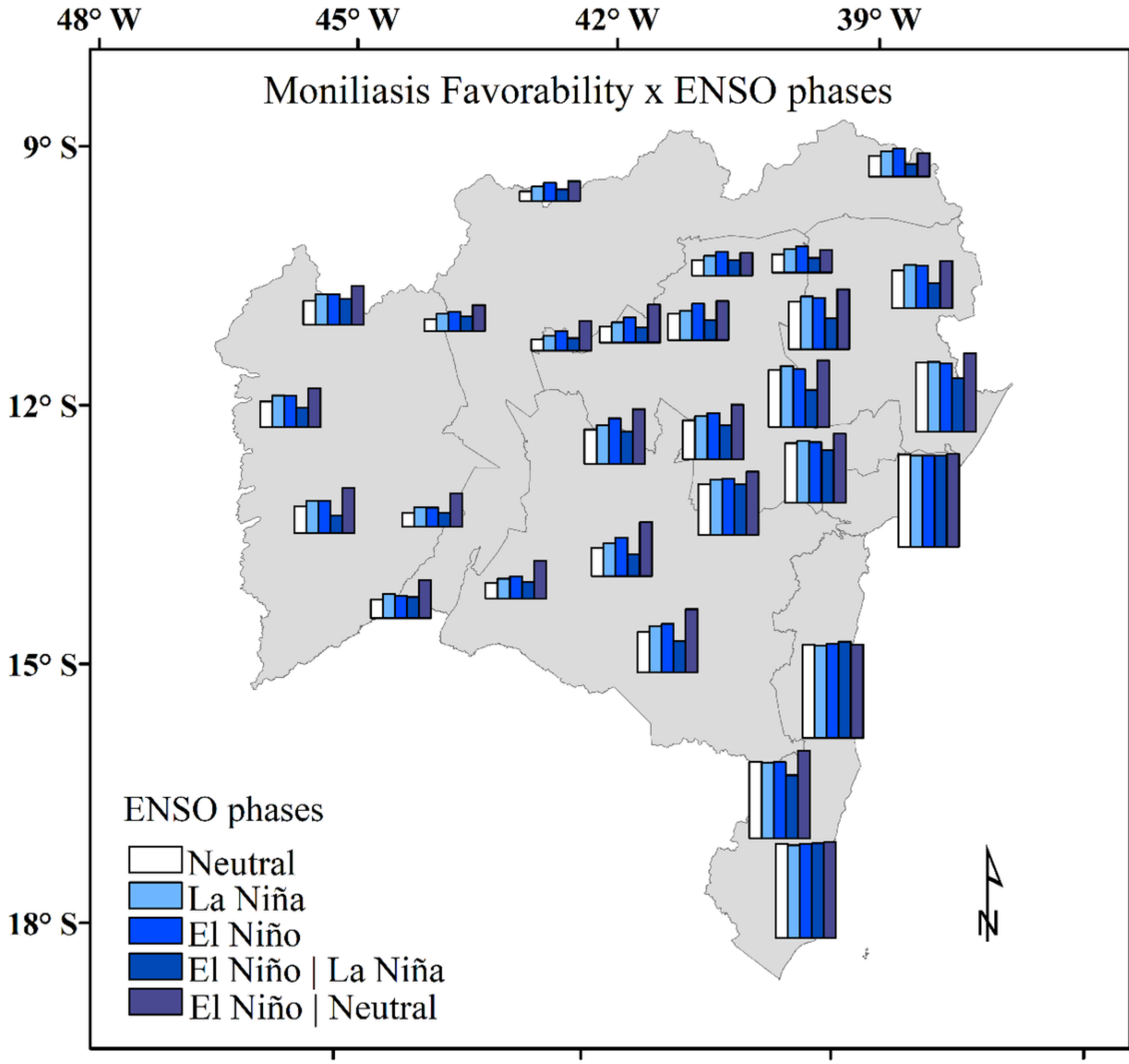

Figure 6

Relative favorability days for cocoa moniliasis occurrence, considering the different phases of El Niño Southern Oscillation (ENSO) – Neutral, La Niña and El Niño, and the transitions of phases – El Niño | La Niña and El Niño | Neutral, during the period from 1988 to 2018. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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