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CROP PROTECTION

A system to map the risk of infection by *Puccinia kuehnii* in Brazil

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ABSTRACT. Orange rust caused by the fungus *Puccinia kuehnii* greatly affects sugarcane and causes millions of tons of losses in production. This condition was first reported in Brazil at the end of 2009. The disease is currently present in most of the countries that produce this crop. The aim of this research was to develop risk maps of *P. kuehnii* infection using temperature and relative humidity data, provided by 389 automatic weather stations throughout the country. A spatial distribution analysis was carried out to assess the number of daily hours of favorable conditions for spore germination in each region. In the central-south region, where the main sugarcane producing states are concentrated, two distinct periods were observed during the three years studied. Higher favorability occurred from October to April, and lower favorability occurred from May to September. The opposite relation was observed on the coast of the north-eastern region, where conditions were more favorable to the disease from May to September. The validation data were confirmed by the results of Pearson's correlation between sugarcane orange rust infection under field conditions and the proposed maps. In conclusion, risk maps obtained using data from automatic weather stations could contribute to the monitoring of the risk of infection by sugarcane orange rust.

Keywords: orange rust; sugarcane; epidemiology; prediction.

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Introduction

Sugarcane (a complex *Saccharum* L. hybrid) orange rust is caused by the fungus *Puccinia kuehnii* (W. Krüger) E. J. Butler. This disease was not present in Brazil and was considered a minor disease in other countries until the end of the 1990s (Braithwaite, Croft & Magarey, 2009). The first reported case of *P. kuehnii* in North America was in Florida, (2007) (Comstock et al., 2008), followed by Guatemala (Ovalle, Comstock, Glynn, & Castlebury, 2008), Nicaragua, Costa Rica (Chavarría et al., 2009), Panama, Mexico, El Salvador (Flores et al., 2009), Cuba (Pérez-Vicente et al., 2010) in Central America and Colombia (Cadavid, Ángel, & Victoria, 2012).

In Brazil, it was first reported near the city of Rincão, São Paulo State, in December 2009. A severe case was discovered in the CV14 (Centaurus) variety in a clone multiplication field and the disease spread throughout southern states of São Paulo and Paraná (Barbasso et al., 2010) and the state of Pernambuco (Chaves et al., 2013).

Environmental conditions directly affect the cultivation of the plants, influencing their growth, development, vitality and susceptibility to disease. They can also affect the survival, sporulation rate, multiplication, dispersion, spore germination and penetration of fungal pathogens. Thus, to develop risk maps for the occurrence of diseases, epidemiological parameters such as temperature and relative humidity are required (Agrios, 2005).

Risk maps enable the prediction of disease occurrence and the production of management programs for diseases. Sentelhas et al. (2016) proposed a predict model for sugarcane orange rust occurrence and severity, for identifying agro-climatic favorability zones for this disease in state of São Paulo and help growers to avoid the use susceptible cultivars in those zones. In this context, based on automatic weather stations throughout Brazil, the aim of this research was to develop risk maps of *P. kuehnii* infection in the whole country using temperature and relative humidity data.

Material and methods

Meteorological data

Hourly meteorological data were obtained from 389 automatic weather stations (Guedes et al., 2013; INMET, 2011) belonging to the Agronomic Institute of Campinas (IAC) and the Brazilian National Institute of Meteorology (INMET) for the years 2008, 2009, and 2010 (Figure 1A). Using these data, it was possible to analyze conditions during the years before and after the disease was first reported in Brazil. Meteorological year data from 2008 and 2009 were used to analyze whether there were conducive orange rust conditions in sugarcane production regions before the first report of the disease in the country.

When information was missing, data on temperature and relative humidity were extrapolated from the closest station data. The geographical locations of the weather stations are shown in Figure 1(A). To provide an idea of the coverage of these stations, suitable sugarcane cultivation areas identified via agroecological zoning carried out by the Brazilian Agricultural Research Agency (Embrapa) are presented in Figure 1(B), allowing identification of the main areas for which risk maps were developed. As can be observed on these two maps, the traditional sugarcane producing central-south region and Northeast coast present a higher concentration of stations.

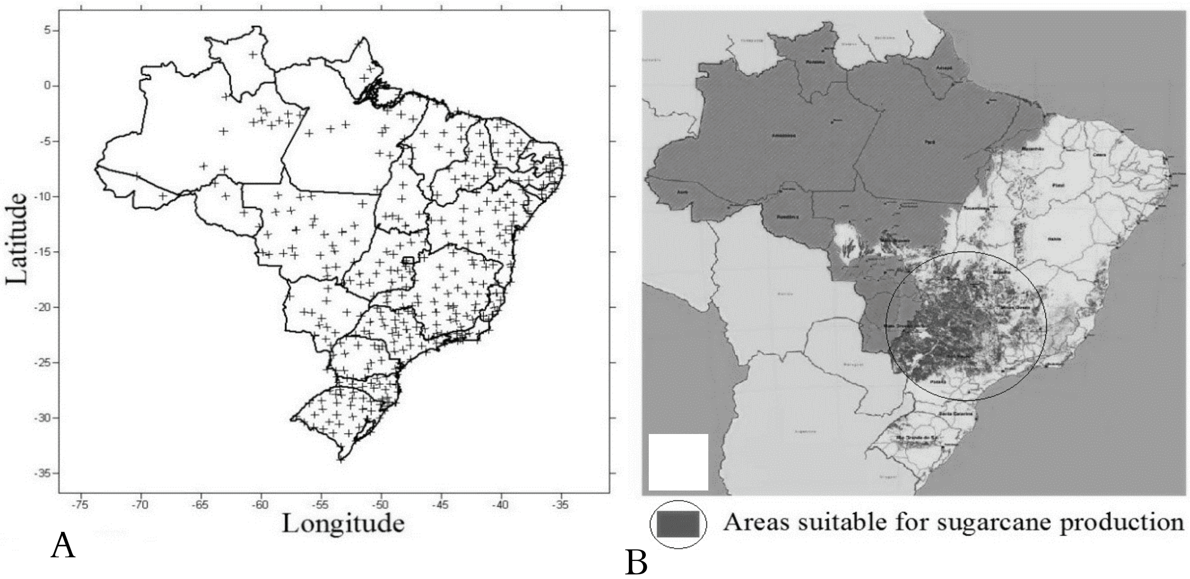

Figure 1. A - Geographical distribution of automatic weather stations of the Brazilian National Institute of Meteorology (INMET) and Agronomy Institute of Campinas (IAC). B - Areas suitable for sugarcane production according to agroecological mapping developed by the Brazilian Agricultural Research Agency (Embrapa). Source: Manzatto, Assad, Baca, Zaroni, and Pereira (2009).

Model used to calculate conditions conducive for sugarcane orange rust in Brazil

Data for temperature and relative humidity provided from the automatic weather stations were used to predict the occurrence of orange rust in sugarcane, using the average number of hours per day with temperatures between 17 and 24°C and humidity greater than 97% was calculated for each location covered by the weather stations. This parameter was used to produce the risk maps using the average of daily favorable hours to *P. kuehnii* germination (DFH SCOR data). To determine the differences between the level of favorability, DFH data were classified by colors into six levels: DFH SCOR data$\in$[0,1[= very low favorability (represented by the color green); DFH SCOR data$\in$[1,2[= low favorability (yellow); DFH SCOR data$\in$[2,3[= moderate favorability (orange); DFH SCOR data$\in$[3,4[= high favorability (red), DFH data$\in$[4,5[= very high favorability (blue); DFH SCOR data$\in$[5,∞] = extremely high favorability (black).

Validation of the used model

Validation of the used model was carried out by an analysis of data obtained in an experiment in Serra Azul, São Paulo State (21° 22'58.42 "S and 47° 31'48.88" W) during cultivation (ratoon phenological stage) of the variety SP84-2025, due to its high susceptibility to sugarcane orange rust. Three experiments were conducted simulating the harvest dates of sugarcane: season I (early harvest), season II (medium harvest) and season III (late harvest).

The experimental area was planted in February 27, 2008. The first cut was held on September 14, 2009, and the second cut (ratton phenological stage) occurred at three different times in 2010: season I (May 5, 2010), season II (August 24, 2010) and season III (October 14, 2010). Each seasonal crop was subdivided into four plots of 42 m^2 each. The three season areas were maintained at the center of the field area that was harvested in September 2009, which acted as an inoculum source.

From sugarcane emergence to harvest, during the three seasons, the severity of orange rust was evaluated monthly, in the leaves (+3) of three plants per plot, with the aid of a diagrammatic scale (Amorim et al., 1987). Evaluators were trained through the software COMBRO developed specifically for training and selection of sugarcane disease severity estimators (Canteri & Giglioti, 1998). After evaluation of the sugarcane orange rust severity, graphics illustrating the disease's progress curve during the three different seasons were created. Then, Pearson's correlation was realized between the data of disease severity and the average of the daily hours favorable to risk infection of *P. kuehnii* (DFH SCOR data).

Construction of the risk zone maps

After validation of the model, Surfer 9.0 (Golden Software) was used to carry out the analysis and construct the risk area maps. Geostatistical analysis of the spatial distribution of DFH SCOR data for each location and its geographical coordinates was performed. The linear model was a mathematical model that best fit the data and was therefore used to later construct semi-variograms and calculate the spatial dependency between weather stations. The Kriging interpolation method was applied to obtain values for the locations lacking climatic data, ensuring that the entire country was covered. These values were then used to construct risk zone maps for each month during 2008, 2009, and 2010.

Results and discussion

Validation of the model

In the model validation data trial, experiments during the first season (early harvest) were started by cutting the third ratton eight months after planting on May 5, 2010. Despite the advanced age of the plantation (eight months), there was a high incidence of sugarcane orange rust, with pustules in an infectious period and producing many *P. kuehnii* spores. The same thing occurred in the August and October samples. Therefore, there was always high-pressure inoculum (spores) of *P. kuehnii* during the validation trial.

The first symptoms of sugarcane orange rust during season I (early harvest) were observed during October with 3.3% severity (Table 1), approximately five months after harvest, on May 5, confirming the existence of an unfavorable initial period to the development of this disease during season I. This finding indicates the use of fungicides during this period was unnecessary. The inoculum potential and the presence of the disease symptoms in all evaluations were estimated indirectly by assessing the disease severity in some source inoculum plants, in which were observed pustules producing a large number of spores in the infectious period, allowing us to confirm that there was always high potential inoculum (spores) in the experimental area during the months from May to August. However, weather conditions recorded during this period were unfavorable to sugarcane orange rust development, preventing or limiting the onset and progress of the disease from May to August in young sugarcane during season I (early harvest).

Sugarcane orange rust progress was slowly from October to November, showing severity values always below to 10% (Table 1). During the same period, the recorded weather conditions were not favorable to disease development, showing a 0.5 value of daily hours being favorable on average, according to the level of favorability in maps, classified as very low favorability. The small increase in disease severity observed during October coincided during the same period with a small increase in the number of favorable hours for *P. kuehnii* spore germination observed in the region. Increasing favorability conditions for the infection occurred from December to April (2008/09 season) and there was also a disease severity increase during this period. The disease peak in the field was registered during February 2011, with an average severity of 30.6% in the sugarcane leaves +3 early harvest (data not shown).

During season II, the first evaluation was during December 2010, showing 16.3% severity (Table 1), the same severity level of season I. Similar results were also observed during the late harvest or season III, with the first evaluation during March 2011. Unlike season I, after observing disease symptoms, there was a sharp increase in sugarcane orange rust during the second and third seasons. The disease increase coincided with weather favorable conditions observed in the region. The progress of the disease was similar for the three seasons' harvest from December 2010 to March 2011, independent of plant age (Table 1).

During May 2011, climatic favorability for the development of sugarcane orange rust was low. There were few hours of conducive conditions for *P. kuehnii* spore germination, with a total of just 18 h during the month, which represented a daily average of only 0.5 favorable hours; consequently, sugarcane orange rust severity decreased during the second and third seasons, as compared to the previous month. During the second season the disease severity decreased to 24.7% and 13.1%, during April and May, respectively. During the third season the average severity observed during April was 26.4% and during July it decreased more than 8.6%.

Table 1. Average of Daily Favorable Hours (DFH) according to the maps, in Serra Azul, São Paulo State from 2008 to 2010, the severity of sugarcane orange rust (October 2010 to July 2011) during the three seasons and Pearson's correlation between average hours of favorability and disease severity.

First season						
Data	2008/2009[a]	2009/2010[a]	-	DFH[a]	Severity[b] season	Pearson's correlation
Oct	0.5	0.5	-	0.5	3.3	
Nov	0.5	0.5	-	0.5	9.5	
Dec	1.5	2.5	-	2.0	11.8	0.80
Feb	3.5	0.5	-	2.0	30.6	
Mar	3.5	1.5	-	2.5	27.1	
Second season						
Data	2008/2009[a]	2009/2010[a]	-	DFH[a]	Severity[b] season	Pearson's correlation
Dec	1.5	2.5	-	2.0	16.3	
Feb	3.5	0.5	-	2.0	27.1	
Mar	3.5	1.5	-	2.5	30.7	0.65
Apr	1.5	0.5	-	1.0	24.7	
May	0.5	0.5	-	0.5	13.1	
Third season						
Data	2008[a]	2009[a]	2010[a]	DFH[a]	Severity[b] season	Pearson's correlation
Mar	1.5	3.5	1.5	2.2	29.3	
Apr	2.5	1.5	0.5	1.5	26.4	
May	0.5	0.5	0.5	0.5	27.7	0.64
Jun	0.5	0.5	0.5	0.5	16.2	
Jul	0.5	0.5	0.5	0.5	8.6	

[a]0 to 1 hour of favorability: very low favorability; 1 to 2: low favorability; 2 to 3: moderate favorability; 3 to 4: high favorability; 4 to 5: very high favorability; over 5: extremely high favorability [b] Values $p < 0,05$.

Therefore, although the calculation of weather favorability to sugarcane orange rust development presented is based solely on conducive conditions for spore germination, it was found that during every month there was a relation between the number of hours with temperatures between 17 and 24°C and a relative humidity greater than or equal to 95% with disease severity during the three seasons. Thus, the proposed model functionality is confirmed for calculating the weather favorability for the development of sugarcane orange rust and correlated with disease severity (Figure 2) mainly when comparing data of severity and favorability directly from weather stations (Figure 3).

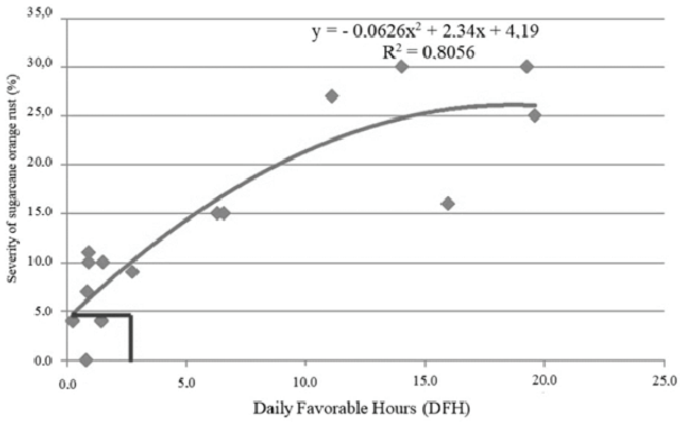

Figure 2. Relationship between daily favorable hours to the occurrence (DFH SCOR) and severity of the sugarcane orange rust considering the three seasons of data.

Analyzing the disease progress during the three seasons, it was found that there is a relationship between the age of the plants (SP84-2025) and their resistance to sugarcane orange rust, as in pathosystem RB83-5486/*Puccinia melanocephala*. The RB83-5486 variety is highly susceptible to rust brown during its first months of plant growth; however, it has adult plant resistance (ontogenetic resistance); in other words, from a certain development stage, the plants of this variety can restrict or even prevent new infections of *P.*

melanocephala, causing a decrease in the severity of rust brown in adult plants (Amorim et al., 1987). This was not evident in the SP84-2025 variety, where the severity of sugarcane orange rust was similar during different stages of development. For example, during March 2011, when the first season of sugarcane was in the maturation phase, the severity of sugarcane orange rust on the leaf (+3) was approximately 27.1%. That same month, recorded severities of 30.7% and 29.3% in the leaves +3 during the second and third seasons occurred, respectively. The correlation data of daily favorable hours (DFH) (according to the maps) and the severity of sugarcane orange rust showed a high correlation of 0.80 during season I and a moderate correlation of 0.65 and 0.64 during seasons II and III, respectively (Table 1).

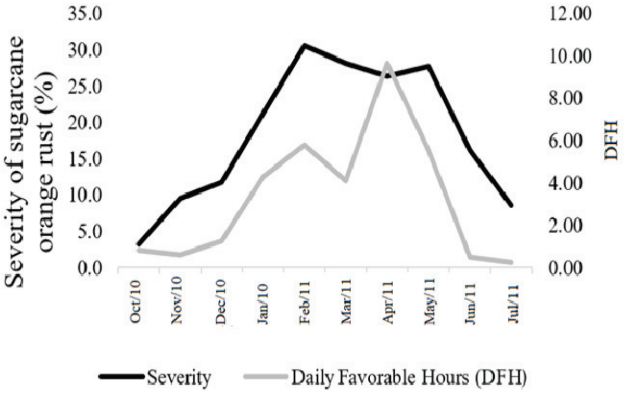

Figure 3. Severity of sugarcane orange rust between October 2010 and July 2011, in Serra Azul city, São Paulo State, Brazil (dark line) and the average of daily hours favorable DFH to *P. kuehnii* spore germination, in Pradópolis, São Paulo State, Brazil (light gray line). Data average of daily hours favorable was based on data from automatic weather stations in Pradópolis, city near Serra Azul.

Favorable data during the 2008 and 2009 seasons show that even though sugarcane orange rust had not been reported in Brazil, conducive conditions for the risk infection of *P. kuehnii* already existed. In Western countries, the disease had been reported only in North (Comstck et al., 2008) and Central America (Ovalle et al., 2008; Chavarría et al., 2009; Flores et al., 2009; Pérez-Vicente et al., 2010).

Risk zone maps

Risk infection maps of *P. kuehnii* were created as a function of average daily number of favorable hours from 2008 to 2010 (Figures 4 to 6). During 2008, a higher number of average daily hours were registered from January to April than for any of the subsequent months. From May 2008, there was a reduction in the favorable zones until September, areas covering the states of Pará, Tocantins and the Northeast (excluding the coast), Central-West, Southeast and South regions. During October 2008, there was a gradual monthly increase in favorable hours, principally along the Brazilian coast, until April 2009, when a phase of less favorability occurred between May and September, mainly in the central-south region and continued until December 2010. Therefore, two distinct periods were observed in the central-south region, the interior of the Northeast, Pará and Tocantins for the three years evaluated as follows: higher favorability from October to April and lower favorability from May to September.

The opposite situation was observed for the coastal region of the Northeast. Conditions of higher favorability were found between April and September. The coastal area with the lowest favorability was found between Salvador in the Bahia State and Maceió in the Alagoas State. High favorability was also observed in the north region during the whole year, mainly in the Amazonas State and, the north of the Pará and Amapá states, where observed averages of over four hours of conducive conditions to orange rust occurred. However, there was a reduction in favorability from January to May and from September to December during 2010 compared to that of the previous years. The north and northeast interior regions are not suitable for the cultivation of sugarcane, as shown in Figure 1B.

Based on the risk zone maps, we can observe conducive conditions to orange rust from September/October to March/April in Brazil's main sugarcane producing areas, concentrated in São Paulo, Minas Gerais, Goiás, Paraná and Mato Grosso do Sul states. In addition to regional and temporal variations, there were observed variations from one year to the next. For example, the period from August to December during 2009 and 2010 was more favorable than the same period in 2008, when favorability reached its most alarming levels during December.

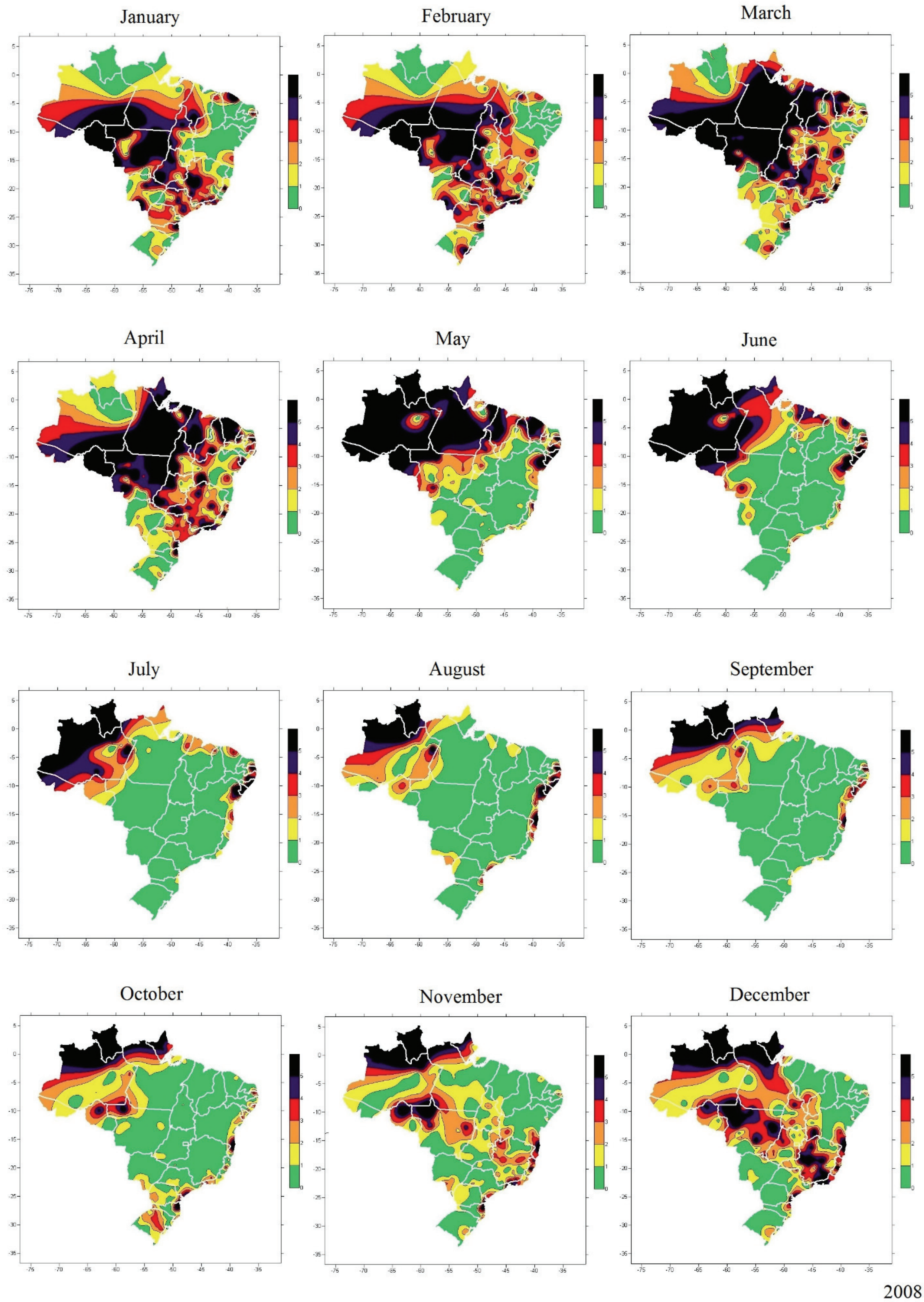

Figure 4. Risk zone maps for *P. kuehnii* infection in Brazil from January to December 2008 developed based on the average of daily favorable hours (DFH) with temperatures between 17 and 24ºC and humidity above 97%. 0 to 1 hours of favorability (green) = very low; 1 to 2 (yellow) = low; 2 to 3 (orange) = moderate; 3 to 4 (red) = high; 4 to 5 (blue) = very high and over 5 (black) = extremely high favorability.

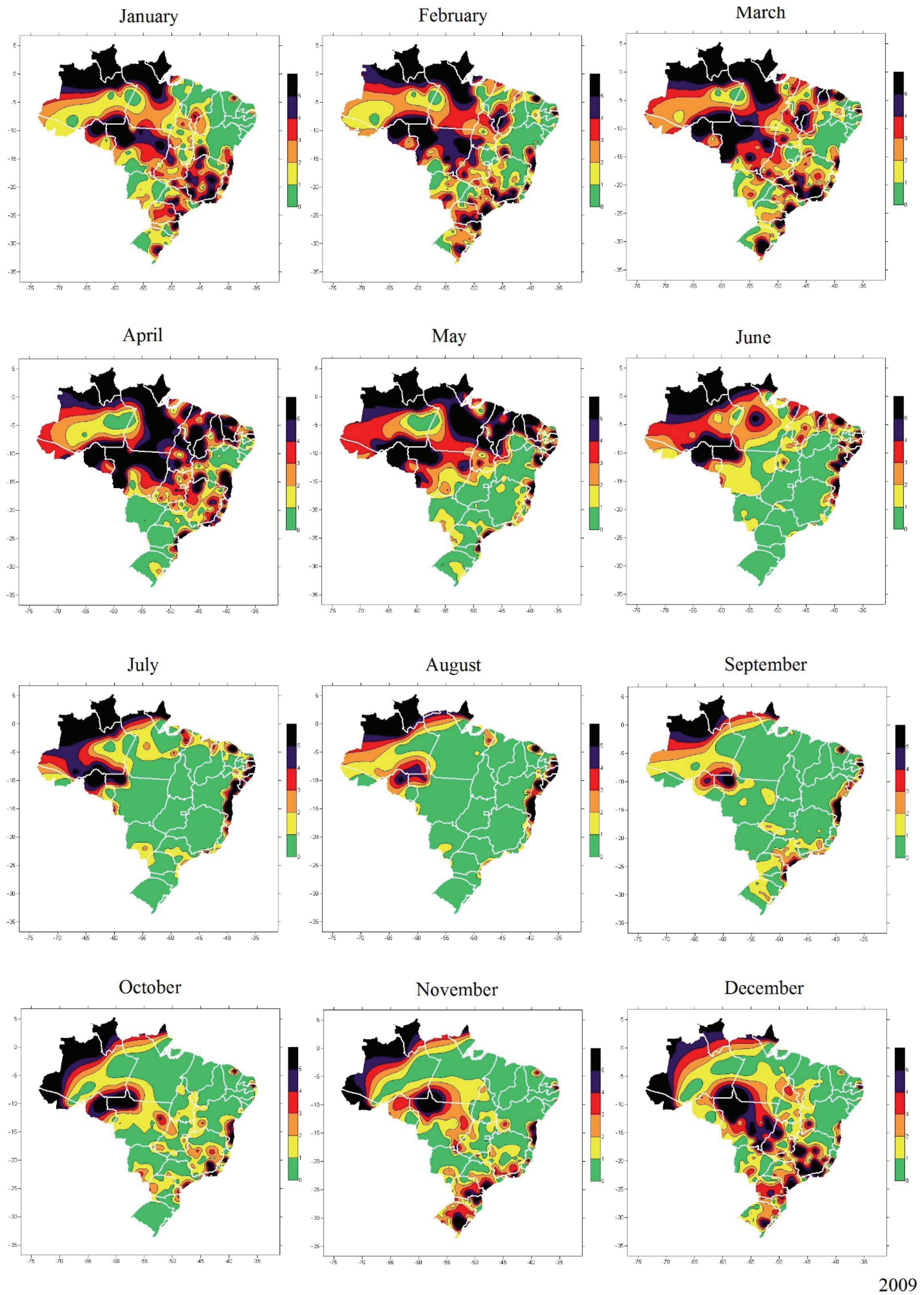

Figure 5. Risk zone maps for *P. kuehnii* infection in Brazil from January to December 2009 developed based on average of daily favorable hours (DFH) with temperatures between 17 and 24°C and humidity above 97%. 0 to 1 hours of favorability (green) = very low; 1 to 2 (yellow) = low; 2 to 3 (orange) = moderate; 3 to 4 (red) = high; 4 to 5 (blue) = very high and over 5 (black) = extremely high favorability.

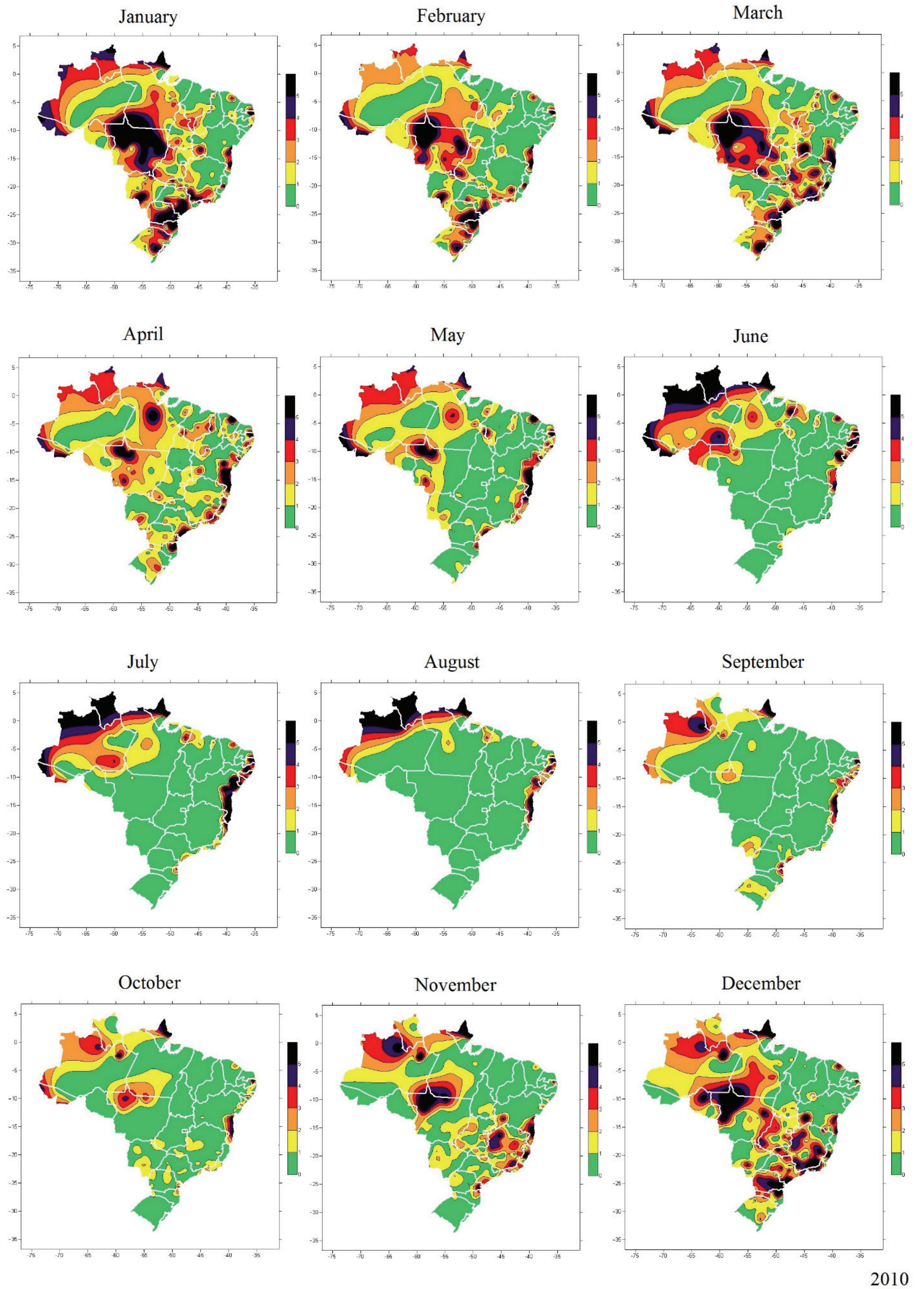

Figure 6. Risk zone maps for *Puccinia kuehnii* infection in Brazil from January to December 2010 developed based on average of daily favorable hours (DFH) with temperatures between 17 and 24°C and humidity above 97%. 0 to 1 hours of favorability (green) = very low; 1 to 2 (yellow) = low; 2 to 3 (orange) = moderate; 3 to 4 (red) = high; 4 to 5 (blue) = very high and over 5 (black) = extremely high favorability.

According to Bergamin Filho and Amorim (2011), any model that predicts the outbreak of a disease using data on climate, hosts or pathogens can be considered to be a disease prediction model. Del Ponte, Godoy, Li, and Yang (2006) reported prediction models for Asian soybean rust in the main Brazilian producing regions. These models identified the most areas favorable to the infection of this fungi using climatic data and could be used as precursors for the development of mapping the risk of disease occurrence. Various studies mapping risk areas have been developed for other crops. Lopes, Barreto, Scaloppi, Barbosa, and Brunini (2008) developed maps for citrus canker in São Paulo State using meteorological data from 2002 to 2005, and reported that the northwest region presented the highest number of days with favorable climatic conditions for the disease. Hamada, Ghini, Rossi, Pedro Junior, and Fernandes (2008) developed maps for grape downy mildew in São Paulo State using climatic data recorded from September to April, the period during which the disease can affect grapevines under development. The cities of Jales, Jundiaí and São Miguel Arcanjo, important grape growing areas in this state, were evaluated.

This study allowed for the quantification of disease severity, both spatially between different state regions and temporally during the study period, adequately differentiating the areas studied. Garcia, Sentelhas, Tapia, and Sparovek (2008) evaluated the climatic risk of potato late blight in the Andes (Venezuela) and developed maps showing that the highest risk of proliferation of the disease occurred during the rainy season (from May to July) and decreased during the dry and transition seasons. Moraes, Peixoto, Jesus Junior, and Cecílio (2011) developed space-time mapping of areas of climatic favorability to coffee rust infection in Brazil using historical averages of temperature and relative humidity data from 1961 to 1990 provided by the Climate Research Unit (CRU). Using these data, monthly maps were created for the climatic favorability to fungi infection. It was concluded that the period of highest climatic favorability was between December and May. This period was classified as "highly favorable" and "favorable" in the country's main coffee producing regions.

Sentelhas et al. (2016) developed risk maps for orange rust in the sugarcane regions of São Paulo State where the risk of this disease is low. The risk in the central and eastern regions of the state varied from moderate to high, coinciding with data from the 2009/2010 yield. Areas with low favorability in the east region match the maps developed during the present study from January to March 2009 and from November 2009 to April 2010. This indicates that simpler models used during the present study, can identify with sufficient accuracy the locations and time periods during which disease management should be implemented to control sugarcane orange rust. The greatest advantages of this method are its speed, simplicity and the low cost of maintaining the weather stations, which only need to collect data on temperature and relative humidity. The maps developed using monthly data from January 2008 to December 2010 demonstrate the variability of the conducive conditions for orange rust as calculated using climatic data.

There are particular features on each map created by Lopes et al. (2008), Hamada et al. (2008), Garcia et al. (2008), Moraes et al. (2011), and Sentelhas et al. (2016) in terms of the methodology, meteorological data, climatic data and mathematical models used, mainly due to differences in favorability among the maps for different diseases and crops, as different environmental and genetic factors influence the pathogen-host relationship and determine the complexity of each different pathosystem. The development and dissemination of these maps on a monthly or weekly basis could contribute toward monitoring and epidemiological studies of orange rust occurrence in sugarcane, as well as to the evaluation of the necessity for disease control, including methods such as avoiding planting susceptible varieties in zones favorable to the disease and promoting the use of chemical control in locations and during time periods of high favorability. Therefore, it is suggested that all sugarcane regions and production units use the practical and effective model to manage orange rust in their crops.

Conclusion

The risk maps obtained using data from automatic weather stations could contribute to the monitoring of the risk infection of sugarcane orange rust and to the development of strategies to control orange rust.

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