University of São Paulo
“Luiz de Queiroz” College of Agriculture

Development and assessment of a warning system for coffee rust management and its use for disease risk evaluation

Fernando Dill Hinnah

Thesis presented to obtain the degree of Doctor in Science. Area: Agricultural Systems Engineering

Piracicaba
2018

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

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EPIGRAPH

"I've missed more than 9000 shots in my career.
I've lost almost 300 games.
26 times, I've been trusted to take the game winning shot and missed.
I've failed over and over and over again, in my life
And that is why I succeed".

Michael Jordan

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RESUMO

Desenvolvimento e aplicação de sistemas de alerta fitossanitário para o manejo da ferrugem do cafeeiro

O cultivo do cafeeiro é de grande importância para o Brasil, sendo cultivado em mais de 2 milhões de hectares. Diversas doenças influenciam a produtividade, sendo a ferrugem do cafeeiro (CLR), a principal. Ocasionada pelo fungo *Hemileia vastatrix*, a CLR é capaz de reduzir a produtividade em até 35%. A estratégia mais comum de controle dessa doença é a aplicação de fungicidas foliares, baseado no período residual e de acordo com a intensidade da doença na região. Este método tradicional não considera a influência do clima no desenvolvimento da doença. Com o objetivo de desenvolver um sistema de previsão (FS) para o manejo da CLR utilizando dados de experimentos de campo obtidos desde 1998, diversas etapas foram realizadas: a) análise epidemiológica; b) relação da taxa de progresso da doença com variáveis ambientais; c) desenvolvimento do FS, visando racionalizar o controle químico; d) avaliação do desempenho do FS, em experimentos de campo; e) geração de índices agro-climáticos de favorabilidade para a ocorrência da CLR nas áreas produtoras de café do Brasil; e f) avaliar efeitos do fenômeno El Niño Oscilação Sul (ENOS) nas epidemias de CLR. Foram analisadas 88 epidemias de CLR, em Varginha, Boa Esperança e Carmo de Minas, MG, sendo o modelo de Gompertz o que resultou em melhor ajuste à curva de progresso da doença. Usando metodologia *stepwise*, as taxas de progresso mensais da doença foram estimadas com regressões lineares múltiplas, baseada em dados de temperatura mínima e umidade relativa do ar. O melhor modelo de estimativa resultou em menos de 9.5% de ocorrências de falso negativos, durante os meses avaliados. Para avaliar o desempenho do FS, dois experimentos foram realizados na safra 2015-16 (Varginha e Boa Esperança, MG) e cinco na safra 2016-17 (Varginha, Boa Esperança, Uberlândia, Buritizal e Campinas). Os tratamentos baseados no FS resultaram em melhor desempenho que o sistema tradicional em seis experimentos, à exceção de Campinas. Este desempenho inferior evidenciou a necessidade de calibração de limiares em diferentes locais, diferentes da região onde o FS foi desenvolvido, devido a sua base empírica. Para avaliar o risco da doença, a taxa de progresso diária foi estimada em 46 locais da região produtora de café, durante as estações de cultivo disponíveis, em uma base de dados históricos de 1961 a 2015, gerando as taxas de progresso acumuladas (CIR). Para cada local e estação, cinco classes com pontuação de Muito Baixo (0) a Muito Alto (4) foram atribuídas, gerando valores de risco. Utilizando regressão linear múltipla, o risco para a CLR foi espacializado em função dos valores de coordenadas geográficas e altitude. Os riscos Médio e Alto foram os mais comuns onde atualmente se cultiva café. No mesmo período de dados meteorológicos, a CIR de 45 locais foi estimada, sendo as estações classificadas em função das possíveis fases de ENOS: El Niño (EN), Neutro (NT) e La Niña (LN). Houve predominio da ausência de efeito do ENOS na CLR no Brasil. Apenas nos estados do PR e SP o EN induziu a uma maior CIR.

Palavras-chave: *Hemileia vastatrix*; Avaliação de risco; Doenças de plantas

ABSTRACT

Development and assessment of a warning system for coffee rust management and its use for disease risk evaluation

Coffee crop is of major importance to Brazil, being cultivated on more than 2 million hectares. It is a strategic commodity for the country, which is the main world producer. Several factors influence the yields, mainly a disease known as coffee leaf rust (CLR), caused by the fungus *Hemileia vastatarix*. This disease can reduce yield up to 35% and the most common strategy for CLR controlling is by spraying fungicides, with interval based on the residual period and according to regional CLR intensity. This traditional way does not consider the climate influence on disease development. With the aim of developing a forecast system (FS) for CLR management, employing weather data from CLR field assessments since 1998, several steps were performed: a) CLR epidemiology analysis; b) correlation between disease progress rates and weather variables; c) development of a forecast system, in order to rationalize chemical control; d) assessment of the FS performance on field trials; e) generation of an agro-climatic index for CLR risk assessment in Brazilian coffee areas; and f) evaluation of possible El Niño Southern Oscillation (ENSO) influence on CLR epidemics. Analising 88 site-season CLR epidemics, from Varginha, Boa Esperança and Carmo de Minas, MG, the best fit was obtained by Gompertz model. Using stepwise method, CLR infection rates were estimated with multiple linear regressions, using minimum temperature and relative humidity as inputs. The model performed well, presenting less than 9.5% of false negatives in the months assessed. To evaluate CLR forecast system, two field trials were performed during 2015-16 season (Varginha and Boa Esperança), and five during 2016-17 season (Varginha, Boa Esperança, Uberlândia, Buritizal, and Campinas). The FS treatments performed better than the calendar spray system in six trials, with the exception for Campinas. The poor FS performance in Campinas evidenced the necessity of FS threshold calibration at sites different from the region where the FS was developed, once it is empirical. In order to assess the risk, the estimated CLR infection rate was evaluated for 46 different sites in Brazilian coffee producing region. Historical weather data since 1961 to 2015 for each site was used to estimate daily values of cumulative infection rate (CIR). Each site and season were classified into five CIR scores from Very Low (score 0) to Very High (score 4). The risk was spatialized using multiple linear regression based on geographical coordinates and altitude. The Brazilian coffee region was classified into four risk classes, being most of them between Medium to High risks in the area currently cultivated with coffee. For the same historical serie, CIR was estimated for 45 locations and then classified by ENSO phases: El Niño (EN); Neutral (NT); and La Niña (LN). A predominant absence of ENSO effect on CLR in Brazil was observed. Only in Paraná and São Paulo states there was ENSO effect, with higher CIR during EN seasons.

Keywords: *Hemileia vastatrix*; Risk assessment; Plant disease

1. INTRODUCTION

Brazil is one important global food producer. In the last FAOSTAT (2017) survey, the country was the world's first coffee, sugarcane, and orange grower. Moreover, it is one of the main soybean, papaya, and maize grower. Coffee has been grown in Brazil since 1779, when the first coffee beans were brought to the country (Favarin et al. 2013). In the second decade of 1800's, Brazil began to stablish as a major player, accounted for 45% of coffee beans produced worldwide in 1845, employing massive slavery labor. In the first fields, plant population was around 1200 trees ha^{-1}, while, nowadays, Brazilian fields commonly have from 4000 to 8000 trees in the same area. This results in yield gains, due to better soil coverage and better distributed photosynthetically leaf area (Guimarães et al. 2013).

The coffee crop is still nowadays an important commodity to the country economy, mainly for Minas Gerais and São Paulo states . The two species cultivated in Brazil, *Coffea arabica* L. and *Coffea canephora* L. are known as arabica and robusta coffee, respectively. In Brazil, arabica is cultivated in around 1.5 million ha (Instituto Brasileiro de Geografia e Estatística (IBGE) 2017a) and has superior drink quality and flavor, with higher prices and demand. Robusta coffee is cultivated in about one third of arabica's area, and has lower quality and prices.

Diseases occurrence is one of the main factors impacting production costs, resulting, when not well addressed, in yield losses. Coffee leaf rust (CLR), caused by *Hemileia vastatrix* Berk. & Br., threatens coffee plantations around the world, including Brazil (Camargo 2010). The usual CLR control strategy is based on fungicides sprays according to a calendar schedule, with the interval between sprays determined by the fungicides residual period (Luaces et al. 2011), and regional necessity. However, the disease intensity is variable from season to season according to their weather characteristics, modifying the fungicides necessity and time of application.

Coffee plants have a biennial phenology characterized by vegetative and reprodutive phases, which occur at the same time in a season, as a consequence of their overlapping (Camargo and Pereira 1994).. The optimum annual average temperature to arabica coffee is between 18 and 22 ºC, which defines the suitable areas for commercial production (Assad et al. 2004). The temperature range favorable to coffee plants are similar to the optimum for CLR, between 18 and 26 ºC, with maximum spores germination rate at 22 ºC (Kushalappa et al. 1983; Zambolim et al. 2005). Coffee plantation cultivated in regions where annual average temperature is below 18 ºC will result in a late berry maturation, which will occur at the same time of new blooming, impairing the harvest process and affecting the next year yield (Camargo and Pereira 1994).

A succesfull coffee plantation is dependent of phenological phases and weather synchronization (Camargo and Pereira 1994), affecting vegetative growth, bud diferentiation, flowering, and grain filling. A well defined dry season, absence of frosts, and mild temperatures are essential factors for achieving high coffee yield and quality. On the other hand, mild temperatures and long periods of leaf wetness duration will favor the occurrence of diseases, mainly CLR, decreasing yields.

CLR epidemics occur in Brazil every year with variable intensity, which is caused mainly by weather variability. The yield losses caused by this disease can be as high as 35% (Zambolim et al. 2005). Symptoms appear on leaves, decreasing photosynthetic area or causing leaf drop, and can persist for two growing seasons, given the biennality of coffee plants (Zambolim et al. 1992).

Despite there are many studies focusing on forecasting or controlling CLR epidemics (Kushalappa et al. 1983; Kushalappa and Eskes 1989; Chalfoun and De Carvalho 1999; Meira et al. 2009; Luaces et al. 2010, 2011), the impact of this disease on coffee plantations remains considerable. Genetic tolerance of arabica coffee cultivars to rust is insufficient, and most fields are still planted with suscetible cultivars. Furthermore, the appearance of new pathogens races, capable of breaking genotype resistance, is another important threat for coffee crop (Garçon et al. 2004). As a result, chemical control is still the most used method to minimize yield losses caused by CLR.

Plant diseases are commonly conditioned by the interaction of three factors: host, pathogen, and environment. Due to the perennial nature of coffee plants and the mild temperatures characteristics of Brazilian producing regions, the biotrophic rust pathogen is perhaps always present in the fields, which help to increase the disease pressure. Consequently, weather becomes a key aspect of CLR epidemiology, modifying disease intensity and, therefore, chemical control needs (Campbell and Madden 1990; Garçon et al. 2004; Meira et al. 2008). Based on that assumption, the hypothesis of this study is that the weather conditions have influence on the CLR occurrence and intensity and that a forecast system for this disease can help the growers to keep it under control during the whole coffee season with a rational fungicide use, since the sprays will be only used when the weather favors the pathogen. Also, a system like that can help to assess the climatic risk in different coffee producing regions allowing a better disease control planning along the seasons.

Therefore, the objectives of this research were: i) to analyse CLR epidemics, through disease progress curves (DPC) from historical Procafé Foundation database; ii) to obtain the relationship between CLR infection rate and weather variables; iii) to develop a forecast system, aiming to rationalize chemical control for this disease; iv) to evaluate the forecast system perfomance under field conditions; v) to generate a CLR agro-climatic risk index, based on the proposed forecasting system and on historical weather series of Brazilian coffee producing regions; vi) to map CLR favorable agro-climatic zones, based on the risk index, for allowing strategic planing of control strategies; and vii) to evaluate the El Niño Southern Oscillation phases influence on CLR intensity, on Brazilian coffee producing regions.

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2. WEATHER-BASED COFFEE LEAF RUST APPARENT INFECTION RATE MODELING

ABSTRACT

Growing 2 million hectares of coffee, Brazil is the major worldwide coffee beans producer. The commodity is mainly cultivated on Minas Gerais and São Paulo states, where 75% of the coffee fields are cultivated with *Coffea arabica,* and the other 25% with *Coffea canephora*. Coffee leaf rust (CLR) is a disease that causes losses due to the decrease on healthy leaf area, thus the yields. This research has as objectives: to determine the best linearization model to estimate the CLR apparent infection rate; to correlate CLR infection rates with weather variables; to develop and assess the performance of weather-based infection rate models, to be used in a disease warning system. On 88 site-seasons the CLR epidemic was analyzed, as well as the progress curves were assessed employing linear, monomolecular, logistic, Gompertz, and exponential linearization models. Using the monthly CLR infection rates obtained with the best fit model, correlations between them and weather variables was done, on different periods of time. Through stepwise methodology, the CLR infection rates were estimated with multiple linear regressions, using the most correlated weather variables. There is a variation on disease intensity according to fruit load (yield). CLR incidence reaches higher values on high yield seasons, above 80%. Under low yield season, the maximum is around 35%. As a consequence, high load seasons demand more attention to CLR control. The Gompertz growth model has the best fit with CLR progress curves. Minimum temperature and relative humidity were the weather variables chosen to compose CLR infection rate forecast system. Those variables are highly correlated to temperature during high humidity periods and number of hours of high humidity periods. The model developed for high yields on narrow rows space has the best CLR infection rate estimation, with false negative occurrences on less than 9.35% of the months assessed, for general field conditions.

Keywords: *Hemileia vastatrix*; Linearization; Gompertz; Estimation

2.1. Introduction

Coffee is one of the most important crops in Brazil, being cultivated on more than 2 million hectares. It is considered a strategic commodity for the country (Souza et al. 2011), since Brazil is the main coffee producer in the world, totalizing 51.37 million 60 kg bags of beans harvested in 2016 growing season (Instituto Brasileiro de Geografia e Estatística (IBGE) 2017a). Currently the average yield in Brazil is around 24 bags of 60 kg ha^{-1} of coffee beans (IBGE 2017).

Coffee crop plantations in Brazil differs from those cultivated in most of other producing countries, which is due to the monoculture cultivation under full sun condition and with a large row spacing (≈ 3.5 m), allowing mechanized operations. At Central America and Colombia, coffee is usually cultivated under shaded agroforestry systems, preventing mechanization (Avelino et al. 2015). While at Central America the coffee fields are mostly on mountainess areas, in Brazil large flatter areas are cultivated. On these areas the mechanization is possible, as with tractor for phytosanitary treatments, as for the harvesting process.

The coffee plants have as characteristic a biennial phenological cycle divided in 6 phases, with annual production alternancy. As described by Camargo and Camargo (2001), in September vegetative growth and vegetative buds formation begins, becoming the 1st phase; the 2nd phase is also vegetative, from April to August, when vegetative buds of the knots are differentiated into reproductive buds, which will become the next phase; 3rd phase is the flowering and grain expansion, from September to December (a year has gone since the first phase, pronouncing the phases overlap); the 4th phase is the grain formation and filling, from January to March; the 5th phase is the grain maturation, with harvest occurring between May to July; and the 6th is the senescence phase, which lasts from July to August.

Among the several factors that threaten coffee plantations, diseases are the main ones. Among these diseases, coffee leaf rust (CLR) caused by *Hemileia vastatrix* Berk. & Br. is the major one all around the world (Camargo and Pereira 1994; Avelino et al. 2015). In Brazil, the yield reductions caused by such disease can be as high as 35% (Zambolim et al. 2005). The most common strategy for controlling CLR is by spraying fungicides, with the interval between sprays based on the residual period of each specific product, and according to regional necessities. This strategy, which is also known as calendar-based system, is normally less efficient than weather-based systems, mainly when fungicide overapplication or lacks on the control happens. To plan sprays based on weather conditions for different diseases is a suitable strategy for improve the efficiency on the control, however it is not commonly done against CLR.

The overlay of two phenological cycles makes 2nd and 5th coffee phases to happen at the same time, resulting in a high competition for carbohydrates between vegetative and reproductive structures. This kind of competition has as consequence variation in the susceptibility of the coffee plants to CLR. During the years with high yields, most part of the carbohydrates generated by photosynthesis are used for filling grains, instead of plant protection. Under such condition, CLR incidence is higher, achieving averages around 70%, while in the years of low yields an average incidence of 30% is expected.

CLR chemical control should be performed on a rational way, having as criteria the weather conditions during the growing season (forecast systems) (Zambolim 2016). However, there are several barriers that prevent the adoption of this approach by the growers. Among them, the difficulty to interact with the systems, the constant change of field disease levels, a period of time to adapt to the system, and the lack of confidence on the models are some examples (Magarey et al. 2002).

According to aforementioned, the hypothesis of this study is that a well-adapted CLR infection rate model, simple to understand, easy to use, accurate and precise, can be useful to develop a disease warning system to rationalize CLR chemical control in the Brazilian producing regions. Therefore, the objectives of this study were:

a) To assess and adjust CLR progress curves for determining the best linearization model to estimate disease apparent infection rate for different plant populations and fruit load (yield);
b) To correlate CLR infection rates with weather variables considering different periods of time for each condition;
c) To develop weather-based CLR infection rate models, considering the most correlated weather variables for each condition;
d) To test the best model with independent data to evaluate its suitability to be used in a disease warning system.

2.2. Material and Methods

2.2.1. Disease assessments

Coffee rust assessments were divided into the different growing situations available for the study, taking into account plant population as rows spacing and yield (hereafter, fruit load). The plant population was 4000 or 8000 plants ha^{-1}, which represents, respectively, rows spacing of 3.5 m x 0.7 m and 2.5 m x 0.5 m. The higher distance between the rows was named as ‘wide’, while the lower distance was named as ‘narrow’. In each field, due to coffee biennial phenology, two fruit loads were possible: high and low. ‘High’ represents more than 30 bags of 60 kg ha^{-1}, while ‘low’ is lower than 10 bags of 60 kg ha^{-1}. Two cultivars, Mundo

Novo and Catuaí, both susceptible to CLR, and the most common genotypes used in Brazil, were considered for the present study.

Considering the combination of two plant populations and two fruit loads, four conditions were assessed: high fruit load, wide space (HW); high fruit load, narrow space (HN); low fruit load, wide space (LW); and low fruit load, narrow space (LN), as normally occur in the Brazilian coffee plantations. The two fruit load were assessed because this is an important factor for CLR incidence, as the disease intensify its incidence under high fruit load seasons, when plants' defense system is less efficient (Kushalappa et al. 1986; Meira et al. 2009).

The CLR incidence data used in this study are from experiments in a Cwb Köppen's climate region (Alvares et al. 2013) conducted since 1998 to 2017 in Varginha (21°34'00" S, 45°24'22" W, 940 m), from 2006 to 2017 in Carmo de Minas (22°10'31" S, 45°09'03" W, 1080 m), and from 2010 to 2017 in Boa Esperança (21°03'59" S, 45°34'37" W, 830 m), all in Southern Minas Gerais, a traditional coffee region, with more than 600,000 ha cultivated with Arabica coffee. In Carmo de Minas only narrow spacing was available, while in Boa Esperança experiments were conducted only under wide spacing. In Varginha, the experiments presented all conditions.

The CLR incidence on leaves was assessed monthly on a non-fungicide treated plot. CLR incidence scores were determined on leaves of the third or fourth knot of branches at the plants middle third in a non-destructive way. The plants were randomly chosen into a zig-zag walking pattern in the area, as recommended by Chalfoun (1997). All the above-mentioned evaluations were conducted by specialists from 'Fundação Procafé'.

2.2.2. Disease progress curves

CLR incidence and the time of each assessment were used to build progress curves (CLRPC), according to Nutter (1997) and Bergamin Filho (2011). A total of 88 site-seasons CLRPC were assessed, 16 seasons in Varginha (times four field conditions), 8 in Carmo de Minas (times two field conditions), and 4 in Boa Esperança (times two field conditions). As first step, CLR incidence was linearized by different models and then plotted against time for later test and selection of the most suitable model to determine apparent infection rate (r). The CLR incidence was linearized by the following models:

Linear: $y = y$ (1)

Monomolecular: $y = \ln (1 / (1-y))$ (2)

Logistic: $y = \ln (y (1-y))$ (3)

Gompertz: $y = -\ln (-\ln (y))$ (4)

Exponential: $y = \ln y$ (5)

where: y is the proportion of leaves sampled with rust symptoms.

Once linearized, disease proportion was estimated by the regression between transformed CLR incidence values and the time. Through this regression, initial inoculum (linearized) and monthly apparent infection rate were determined, respectively represented by linear (a) and angular (b) coefficients of the regression.

For choosing the best fit model, the following statistical indicators were applied, as recommended by Nutter (1997) and Bergamin Filho (2011): mean bias error (MBE), mean absolute error (MAE), root mean square error (RMSE), coefficient of determination (R^2), Willmott's Agreement Index 'd' (Willmott 1981), and the Confidence Index 'c' (Camargo and Sentelhas 1997).

2.2.3. Correlation between coffee leaf rust apparent infection rate and weather variables

The weather variables during the experimental periods in each location were obtained by automatic weather stations, with data recorded every 30 minutes. The following weather variables were recorded: maximum, minimum temperatures; relative humidity; and rainfall. As leaf wetness duration data were not available, it was estimated based on the number of hours with relative humidity above 80% and 90% (Sentelhas et al. 2008; Rowlandson et al. 2015).

From the weather variables measured on the automatic station, other specific disease driving variables were derived, as presented in Table 1. The weather data were organized in a monthly basis to be compatible with the available CLR infection rate. Correlations between CLR infection rates, determined by the best fitting model and weather variables were assessed through the Pearson's coefficient of correlation, considering CLR apparent infection rate as dependent variable and weather variables from Table 1 as independent ones.

Table 1. Weather variables used in the correlations with coffee leaf rust apparent infection rate, in a monthly basis.

Variable	Definition
Tmed	Average temperature (°C)
Tmin	Minimum temperature average (°C)
Tmax	Maximum temperature average (°C)
Rainfall	Total rainfall (mm)
NDR≥1mm	Number of days with rainfall ≥ 1 mm
NDR≥20mm	Number of days with rainfall ≥ 20 mm
RH	Average relative humidity (%)
$NhRH_{90\%}$	Number of hours with relative humidity ≥ 90%
$NhRH_{80\%}$	Number of hours with relative humidity ≥ 80%
$T\_RH_{90\%}$	Average temperature on periods with relative humidity ≥ 90% (°C)
$T\_RH_{80\%}$	Average temperature on periods with relative humidity ≥ 80% (°C)
$NDRH_{90\%}$≥6h	Number of days with NhRH≥90% equal or above 6 h.
$NDRH_{80\%}$≥6h	Number of days with NhRH≥80% equal or above 6 h.

The correlations were done considering three different time periods: 0-30d (from 0 to 30 days before incidence assessment); 30-60d (from 30 to 60 days before incidence assessment); and 60-90d (from 60 to 90 days before incidence assessment). These periods used for correlations were chosen in accordance with the long latency period of *Hemileia vastatrix,* which lasts from 25 to 40 days (Kushalappa et al. 1983). Pearson's coefficient was used to evaluate the correlations between weather variables and CLR infection rates ($P < 0.01$). The correlation significance was performed using the function 'cor.test' in R. The same procedure was used to correlation between weather variables.

2.2.4. Coffee leaf rust apparent infection rate weather-based models

After obtaining Pearson's correlation coefficient for the relationship between CLR infection rate and weather variables for the three periods of time, the weather-based models were developed for each of the four conditions of fruit load and rows space. The stepwise procedure was applied to select the best variables to compose the simple or multiple regression models for estimating CLR apparent infection rate.

With the aim of using different months for development and validation, the dataset of each condition was divided. The number of months for model development, and validation, in each model, respectively, was: HN = 259; 44; LN = 259; 44; HW = 215; 63; LW = 215; 63.

Each model was validated with the same field conditions than the development, i.e.: HN model was validated with HN months not used for its development.

2.2.5. Statistical Analysis

The CLR infection rate predictors performance was evaluated by contingency tables similar to Duttweiler et al. (2008), moreover using RMSE, MAE, MBE and the coefficient of determination (R^2) between estimated and observed incidence. On these contingency tables, four different classes were possible: True Positive: when an observed increase on CLR incidence was estimated as an increase on a specific threshold; True Negative: when an decrease on CLR incidence was estimated as an decrease on a specific threshold; False Positive: when an observed decrease on CLR incidence was estimated as an increase on a specific threshold; False Negative: when an observed increase on CLR incidence was estimated as an decrease on a specific threshold.

On the contingency table, the thresholds of 5 and 10 percental points (p.p.) were chosen according to the suggestion by Zambolim et al. (1997) and Kushalappa et al. (1984), respectively, to use as risk limit on CLR control, also used on Meira, Rodrigues, and Moraes (2009) to model performance assessment. With the aim of choosing one only model for CLR infection rate estimation on different field conditions, the statistical indicators and new contingency tables were obtained. This model was validated on the four possible conditions. In this case, high and low fruit loads were validated on 107 months datasets.

2.3. Results and Discussion

2.3.1. Coffee leaf rust epidemic

The CLR presented different intensity according to fruit loads (Figures 1 to 3). In Varginha, moreover the fruit loads, it is possible the comparison between wide and narrow rows space. A small difference on the CLRPC increase during the first months (Figure 1A and 1B) is visible for rows space comparison. The epidemic onset is slightly favorable due to the proximity of the canopy leaves in the narrow space. The median was higher on January, February, and March on narrow space, however, after this value, the wide space has highest medians, and the total epidemic is similar. The larger healthy tissues available on wide space are the possible cause to this later progress. Moreover, on this moment of the growing season inoculum source is abundant. The median maximum incidence value is above 80%.

On low fruit load conditions (Figure 1C and 1D), both wide and narrow spaces presented low incidence values, in comparison to high fruit loads. The median was lower than 35%, and the third quartile rarely ever reaches 40%. The epidemic onset was visible in December, either on wide and narrow space. As under high fruit load condition, the maximum value was reached at first on narrow space, however keeping a similar intensity until the end of the season.

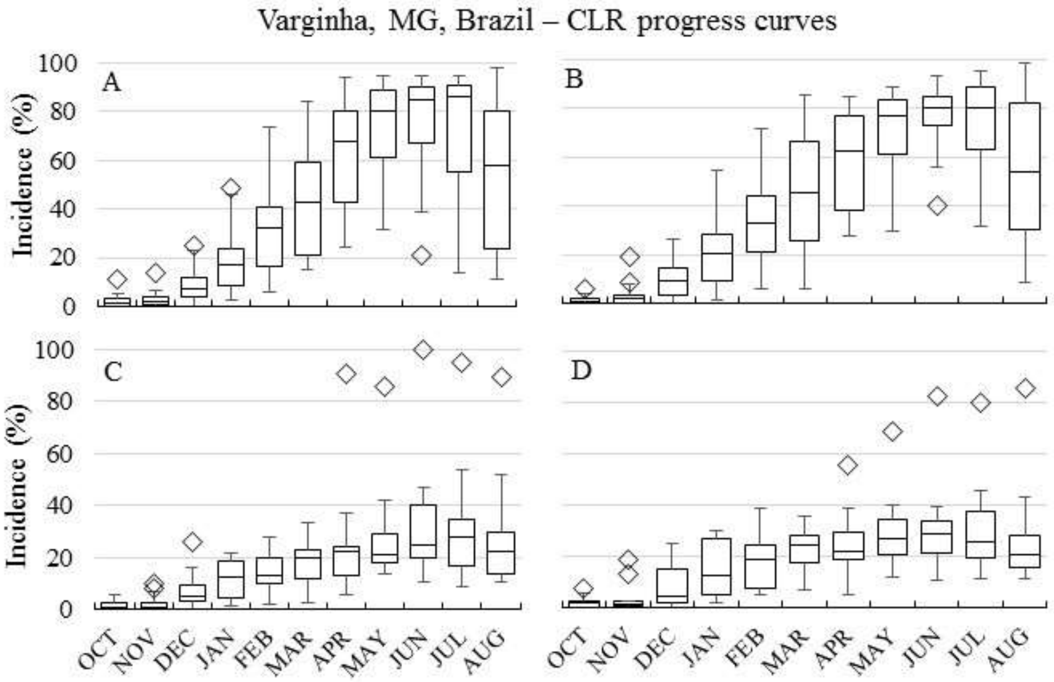

Figure 1. Box-plot of coffee leaf rust progress in four different field conditions in Varginha, Minas Gerais, Brazil. A = high fruit load, wide space; B = high fruit load, narrow space; C = low fruit load, wide space; D = low fruit load, narrow space. Rhombuses are the outliers.

In Carmo de Minas and Boa Esperança (Figures 2 and 3) the comparison for space between rows is not possible. Those sites had only narrow and wide space, respectively. Both sites present high incidence values for high fruit loads, similar to Varginha. Other researches showed the high correlation between CLR intensity and fruit load (Japiassú et al. 2007; López-Bravo et al. 2012; Neto et al. 2014).

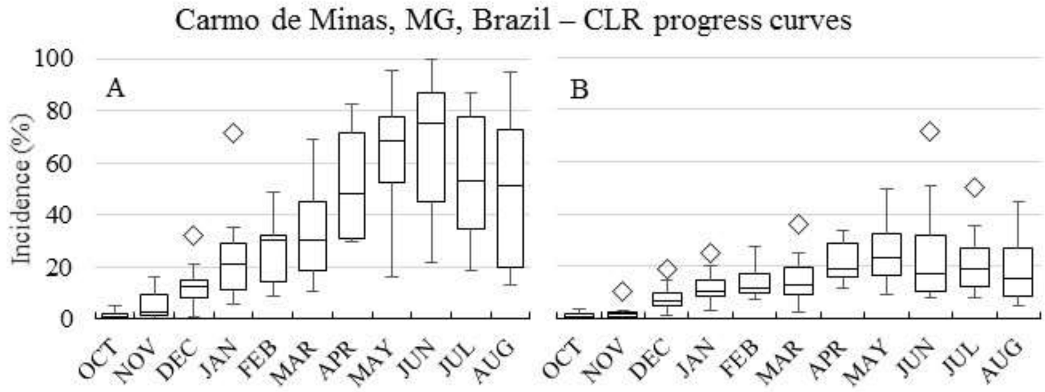

Figure 2. Box-plot of coffee leaf rust progress in four different field conditions in Carmo de Minas, Minas Gerais, Brazil. A = high fruit load, narrow space; B = low fruit load, narrow space.

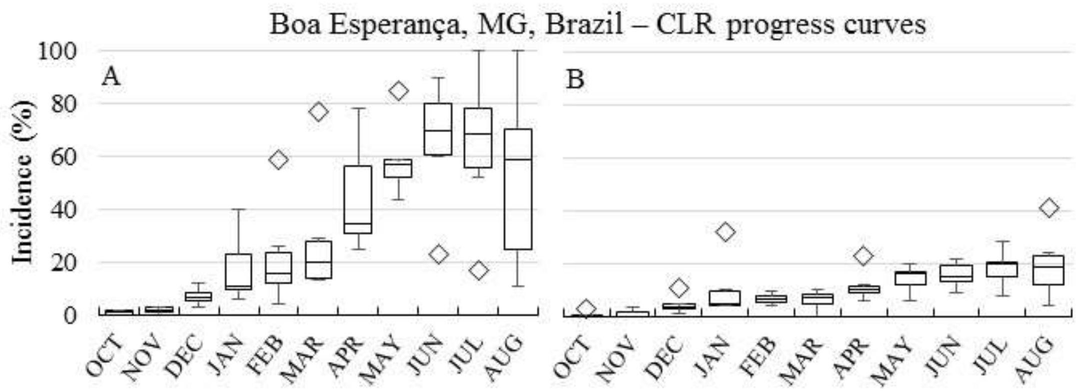

Figure 3. Box-plot of coffee leaf rust progress in four different field conditions in Boa Esperança, Minas Gerais, Brazil. A = high fruit load, wide space; B = low fruit load, wide space.

According to the progress curves in Figures 1 to 3, the high load seasons are considered as the most important, due to several aspects, hereafter explained: 1) the management of CLR is pivotal in these seasons, to keep healthy leaves on the present season and to the next season. In the cases of high defoliation (high load seasons, without CLR control), blooming efficiency is negatively affected (Godoy et al. 1997). In this case, photosynthesis decreases as a consequence of reduced leaf area, reducing the number of active flowers, which reduces potential yield of the next season; 2) currently in Brazil there is a practice of using a ‘zero season’. This method is applied when growers focus on obtaining maximum yields during the high fruit load seasons, making a specific pruning known as ‘skeleton’ that results in no harvest and production in the next season. The outcome are more profitable fields, as a consequence of the low investment on seasons with low yield potential;

3) even in the cases when growers keep the low fruit load seasons, as the incidence is low (Figures 1 to 3), the CLR management is easier. The fungicides that are recommended have a residual period ranging from 60 days to 90 days, according to the dose, which is enough to keep the low yields epidemy under control.

2.3.2. Coffee growth models' analysis

The growth models expected to fit better CLR epidemic would be logistic and Gompertz, due to the polycyclic characteristics of *Hemileia vastatrix* pathogen (Berger 1981). Gompertz sigmoidal shape with inflection point around 37% (1/e) of disease intensity differs from the perfect sigmoidal shape of logistic (inflection point on 50%). The infection rate from the Gompertz model is more accelerated in the epidemic onset, reducing after 37%, due to the limitation of healthy tissue, as shown on Figures 1 to 3. The selection is result of the higher coefficient of determination (R^{*2}) and lower errors (both MAE and MBE) of Gompertz model (Table 2, Figure 4), as recommended by Campbell and Madden (1990), Nutter (1997), and Bergamin Filho (2011).

Table 2. Statistical indexes for performance assessments of five different linearization models for coffee leaf rust infection rate. Dataset from Varginha, Carmo de Minas and Boa Esperança, all placed on Minas Gerais, Brazil.

Model	R^2	R^{*2}	RMSE	MBE	MAE	d index	c index
Linear	0.900	0.856	0.091	0.022	0.072	0.929	0.689
Monomolecular	0.835	0.765	0.096	0.040	0.066	0.936	0.776
Logistic	0.834	0.937	0.079	-0.010	0.045	0.928	0.795
Gompertz	0.868	0.958	0.050	0.000	0.037	0.957	0.848
Exponential	0.780	0.706	0.200	0.025	0.111	0.842	0.619

R^2: coefficient of determination; R^{*2}: coefficient of determination between disease proportion estimated and observed, on the different models; RMSE: root mean square error (percent points, p.p.); MBE: mean bias error (p.p.); MAE: mean absolute error (p.p.); d index: Willmott's Agreement Index; and c index: Confidence Index.

MBE equal zero means no trend, with MAE randomly distributed. The conjunction of these values presents the aggregation pattern of Figure 4D, resulting on higher R^{*2}. Willmott Agreement Index 'd' shows a close to perfection accuracy between observed and estimated data, while Confidence Index 'c' return a 'Very Good' concordance (Camargo and Sentelhas 1997).

A large DPC's range is required for this assessment due to the different possible shapes from the environment characteristics, i.e. favorable conditions during the whole season trend to result on sigmoidal shapes for polycyclic diseases. However, a predominant favorability at the beginning of the season can result in a monomolecular characteristic shape, even for a polycyclic pathogen.

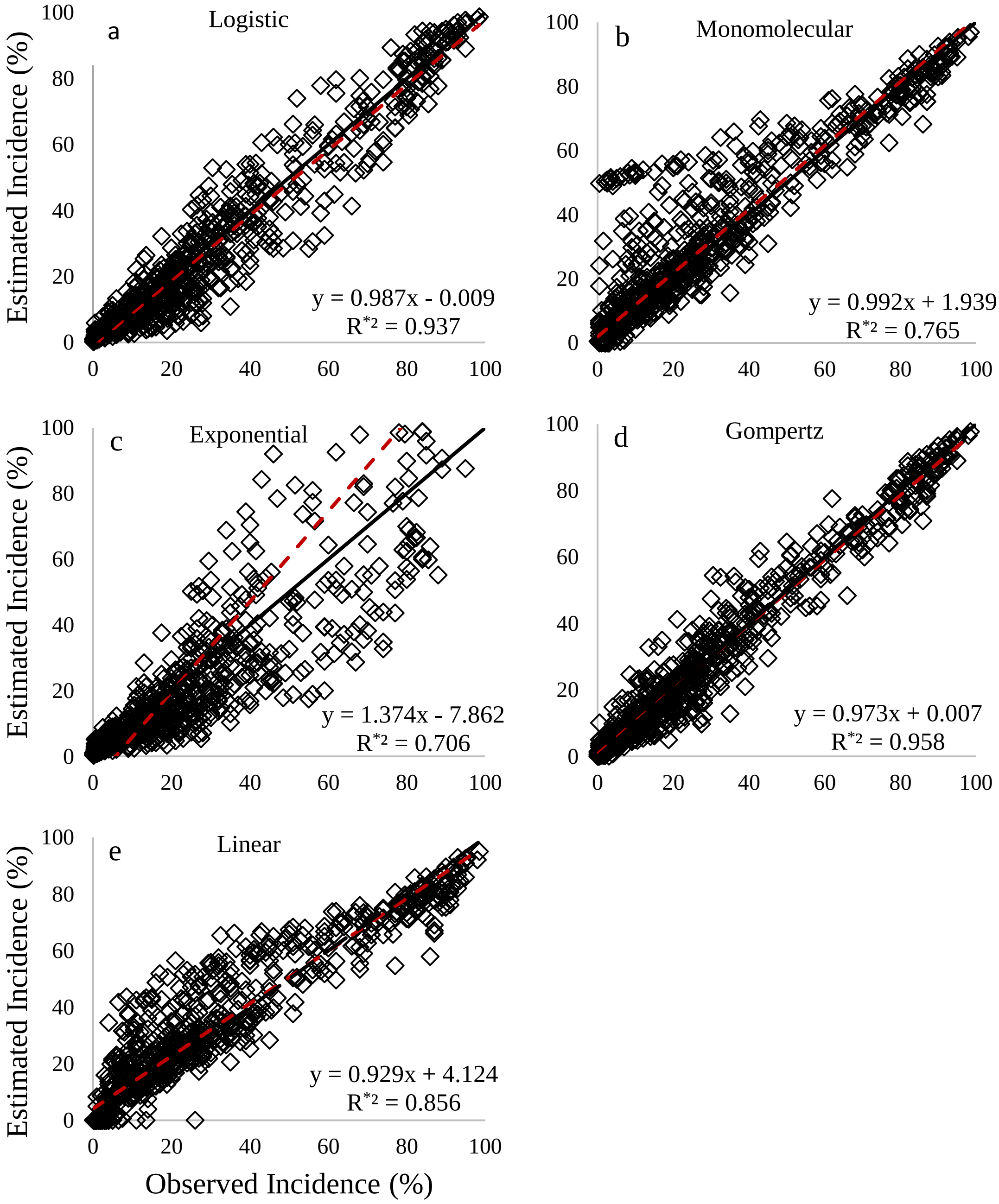

Figure 4. Relationship between observed and estimated incidence of coffee leaf rust by logistic (a), monomolecular (b), exponential (c), Gompertz (d) and linear (e) models. Trend line (dashed) and 1:1 (straight line).

2.3.3. Weather variables *vs* CLR apparent infection rate

The Pearson's correlation coefficients between weather variables and CLR infection rate obtained are presented in Table 3. The most important variables that affect CLR infection rate are the ones with interference on pathogen germination, infection and colonization process. Similar to Wallin (1962) and Madden, Pennypacker, and MacNab (1978), the leaf wetness duration (estimated as function of RH) and the temperature on this period are the most important variables.

Table 3. Pearson's correlation between monthly coffee leaf rust apparent infection rate and weather variables. HW = high fruit load, wide space; HN = high fruit load, narrow space; LW = low fruit load, wide space; and LN = low fruit load, narrow space. Period assessed before leaves symptoms: 0-30d is from 0 to 30 days before incidence assessment; 30-60d is from 30 to 60 days before incidence assessment; 60-90d is from 60 to 90 days before incidence assessment. Dataset from Varginha, Carmo de Minas and Boa Esperança, all located in Minas Gerais, Brazil.

Weather variables	Field conditions Period assessed before leaves symptoms					
	0-30d	30-60d	60-90d	0-30d	30-60d	60-90d
		HN			LN	
Tmed	0.064	0.239*	0.389*	0.209*	0.244*	0.269*
Tmin	0.154	0.344*	0.440*	0.260*	0.322*	0.302*
Tmax	-0.019	0.119	0.294*	0.138	0.144	0.205*
Rainfall	0.221*	0.321*	0.360*	0.260*	0.365*	0.199*
NDR≥1mm	0.202*	0.354*	0.394*	0.257*	0.383*	0.241*
NDR≥20mm	0.161*	0.264*	0.341*	0.194*	0.304*	0.186*
RH	0.396*	0.465*	0.334*	0.285*	0.337*	0.169*
NhRH$_{90\%}$	0.362*	0.432*	0.355*	0.268*	0.309*	0.154
NhRH$_{80\%}$	0.388*	0.455*	0.333*	0.272*	0.322*	0.162*
T_RH$_{90\%}$	0.194*	0.381*	0.453*	0.272*	0.334*	0.294*
T_RH$_{80\%}$	0.213*	0.394*	0.452*	0.284*	0.345*	0.295*
NDRH$_{90\%}$≥6h	0.384*	0.431*	0.307*	0.253*	0.302*	0.131
NDRH$_{80\%}$≥6h	0.351*	0.390*	0.246*	0.264*	0.280*	0.094
		HW			LW	
Tmed	-0.054	0.200*	0.411*	0.138	0.189*	0.249*
Tmin	0.051	0.318*	0.481*	0.223*	0.271*	0.263*
Tmax	-0.139	0.075	0.296*	0.050	0.089	0.197*
Rainfall	0.143	0.316*	0.368*	0.268*	0.302*	0.124
NDR≥1mm	0.085	0.293*	0.393*	0.277*	0.346*	0.156
NDR≥20mm	0.064	0.194*	0.270*	0.134	0.222*	0.066
RH	0.399*	0.492*	0.392*	0.303*	0.271*	0.054
NhRH$_{90\%}$	0.386*	0.452*	0.368*	0.289*	0.233*	0.010
NhRH$_{80\%}$	0.388*	0.480*	0.371*	0.299*	0.266*	0.035
T_RH$_{90\%}$	0.094	0.358*	0.502*	0.241*	0.270*	0.261*
T_RH$_{80\%}$	0.119	0.384*	0.515*	0.255*	0.290*	0.247*
NDRH$_{90\%}$≥6h	0.391*	0.432*	0.295*	0.246*	0.192*	-0.029
NDRH$_{80\%}$≥6h	0.381*	0.400*	0.194*	0.217*	0.189*	-0.014

Asterik (*) indicate that the correlations are significant at $P \leq 0.01$.

To HN conditions, RH, NhRH80%, T_RH$_{80\%}$, T_RH$_{90\%}$, and Tmin had the highest correlations values. To HW conditions, the highest values are for T_RH$_{80\%}$, T_RH$_{90\%}$, RH, Tmin, and $NhRH_{80\%}$. In LW conditions, NDR≥1mm, RH, Rainfall, $NhRH_{80\%}$, $NhRH_{90\%}$were important variables. In LN conditions, the NDR≥1mm, Rainfall, $T\_RH_{80\%}$, RH, $T\_RH_{90\%}$, and Tmin have shown higher correlation coefficients.

Several authors found similar weather influence on CLR epidemic patterns. Rainfall and minimum temperature were the meteorological variables that most explained the CLR variation in the study conducted by Kushalappa and Chaves (1980). Rainfall had higher correlation with long time before the symptoms, as 56 and 42 days. Minimum temperature presented high correlation in the same periods, however not as high as rainfall (Kushalappa and Chaves 1980).

Kushalappa, Akutsu, and Ludwig (1983) used periods of free water on leaves and temperature to predict CLR infection rates. Meira, Rodrigues, and Moraes (2009) found important the temperature during periods of high relative humidity (≥95%) and the RH, on predicting CLR infection rates. The variables related to the temperature during the leaf wetness period, and the length of this period are usually correlated to disease progress, due to their importance on the infection process. Those variables are important for other several disease forecasting models, as *Alternaria solani* in tomato (Madden et al. 1978), *Pyricularia oryzae* in rice (Kim et al. 1988), and *Phytophtora infestans* in potato (Wallin 1962).

2.3.4. Coffee leaf rust infection rate estimation models

Using the highest correlation weather variables for each condition, models were developed. For the HN and LN forecast models, Tmin and RH were the variables selected. According to the correlation shown in Table 4, these variables represented the influence of the temperature during LWD, and the LWD, respectively, on an indirect way. For HW model, Tmed and RH were also selected (a straight difference between Tmed and Tmin) and for LW, the NDR≥1mm was the only variable to describe CLR infection rate variability. The models generated are following, and the variables have been chosen using stepwise selection.

$r_{HN} = -1.293 + 0.019\ Tmin_{(30\text{-}60d)} + 0.017\ RH_{(30\text{-}60d)}$ r = 0.516* n = 259

$r_{LN} = -0.635 + 0.018\ Tmin_{(30\text{-}60d)} + 0.006\ RH_{(30\text{-}60d)}$ r = 0.382* n = 259

$r_{HW} = -1.842 + 0.027\ Tmed_{(30\text{-}60d)} + 0.020\ RH_{(30\text{-}60d)}$ r = 0.532* n = 215

$r_{LW} = 0.013 + 0.0155\ NDR{\geq}1mm_{(30\text{-}60d)}$ r = 0.363* n = 215 where: Tmin = minimum temperature average (°C); RH = average relative humidity (%); Tmed = average temperature (C°); NDR≥1mm = number of days with rainfall ≥ 1 mm; 30-60d is from 30 to 60 days before incidence assessment. HW = high fruit load, wide space; HN = high fruit load, narrow space; LW = low fruit load, wide space; and LN = low fruit load, narrow space. r = Pearson's correlation coefficient. Asterisk (*) indicate that the regressions were significant at the P≤0.01 level. n = number of observations in the dataset.

The time period of the variables used on the models comprehends the majority of the variables with high correlation to CLR infection rate, from 30 to 60 days before disease symptoms. It is related to the latency period of CLR from around 25-30 to more days (Moraes et al. 1976; Zambolim et al. 2005). Moreover, allows a period for management, before the disease symptoms onset. This period for management comprehends acquiring weather data, consisting them, run the model, send a warning to growers, their plan to spray, good weather to spray (i.e.: a week with rainfall can delay the spray on 7 days) and spray.

The Tmin, RH, and Tmed are present on three of the models, while NDR≥1mm is present only for r_{LW} estimation. Only the last variable has poor spatial correlation, becoming necessary its measure at each site where the estimation models can be uses. The first variables have good spatial correlation (Xavier et al. 2015), and are possible to be estimated on sites surrounding weather stations. Meira, Rodrigues, and Moraes (2008) obtained a decision tree for CLR forecast, having the temperature during the above 95% of RH period as the most important predictor. This variable is followed by relative humidity, minimum and maximum temperatures on the decision tree knots of their study, similar with the presented results.

When trying TOM-CAST models, Pitblado (1992) and Gillespie, Srivastava, and Pitblado (1993) had problems with the weather data necessary for the model. Then, the preference to use in the models is for easy measured and with low spatial variability variables. This choice has the goal of making useful models on areas where there are no weather stations. However, those data can be estimated throughout weather stations network. As leaf wetness duration (LWD) and rainfall has high spatial variability (Thomas et al. 2002) their use can be an issue. Moreover, LWD related variables are not directly measured on standard weather stations, and when measured, there is a lack of measurements standard (Rowlandson et al. 2015). Therefore, when the forecast capability was not diminished, those variabilities were deferred.

The weather variables presented strong correlation among them (Table 4). Their correlations can be grouped on temperatures related (1), rainfall related (2), and relative humidity related (3). Following the same order, the correlations shows: 1) temperatures are related with temperature during the periods of high relative humidity (T_RH$_{80\%}$ and T_RH$_{90\%}$; 2) NDR≥1mm is related with temperature during high relative humidity periods (T_RH$_{80\%}$ and T_RH$_{90\%}$); 3) the relative humidity is highly related to the amount of hours with high relative humidity (NhRH$_{80\%}$ and NhRH$_{90\%}$), a variable used as a way for leaf wetness duration knowledge (Sentelhas et al. 2008; Rowlandson et al. 2015), as well as the number of days with NDRH$_{80\%}$>6h and NDRH$_{90\%}$>6h.

Table 4. Pearson's correlation among weather variables used for coffee leaf rust infection rate estimation, in a monthly basis.

	Tmed	Tmin	Tmax	RH	Rainfall	NDR≥1mm	NDR≥20mm	NhRH$_{90\%}$	NhRH$_{80\%}$	T_RH$_{90\%}$	T_RH$_{80\%}$	NDRH$_{90\%}$≥6h	NDRH$_{80\%}$≥6h
Tmed	1												
Tmin	0.99	1											
Tmax	0.99	0.97	1										
RH	0.16	0.16	0.15	1									
Rainfall	0.46	0.48	0.43	0.58	1								
NDR≥1mm	0.53	0.56	0.49	0.63	0.91	1							
NDR≥20mm	0.4	0.42	0.37	0.49	0.92	0.77	1						
NhRH≥$_{90\%}$	0.21	0.21	0.21	0.91	0.57	0.62	0.5	1					
NhRH≥$_{80\%}$	0.19	0.19	0.19	0.92	0.56	0.6	0.48	0.97	1				
T_RH≥$_{90\%}$	0.9	0.9	0.88	0.54	0.66	0.75	0.57	0.54	0.53	1			
T_RH≥$_{80\%}$	0.89	0.9	0.87	0.57	0.66	0.74	0.57	0.56	0.55	0.99	1		
NDRH$_{90\%}$≥6h	0.14	0.13	0.14	0.9	0.49	0.55	0.41	0.92	0.89	0.47	0.49	1	
NDRH$_{80\%}$≥6h				0.85	0.38	0.4	0.32	0.74	0.8	0.33	0.37	0.81	1

Tmed = average temperature; Tmin = minimum temperature average; Tmax = maximum temperature average; Rainfall = Total rainfall; NDR≥1mm = Number of days with rainfall ≥ 1 mm; NDR≥20mm = Number of days with rainfall ≥ 20 mm; RH = average relative humidity (%); NhRH90% = Number of hours with relative humidity ≥ 90%; NhRH80% = Number of hours with relative humidity ≥ 80%; T_RH90% = Average temperature on periods with relative humidity ≥ 90% ; T_RH80% = Average temperature on periods with relative humidity ≥ 80%; NDRH90%≥6h = Number of days with NhRH≥90% equal or above 6 h; NDRH90%≥6h = Number of days with NhRH≥80% equal or above 6 h. Values not shown were not significant at P ≤ 0.01.

2.3.5. Performance of coffee leaf rust infection rate estimation models

Both HN and HW have similar performance, based on lower errors associated and high determination coefficient (Table 5). HW has higher bias (MBE), while on HN it is close to zero, moreover the trend of HW errors are for False Negative conditions (Table 6), underestimating the incidence values. Their MAE and R^2 were similar, 0.820 and 0.810, respectively. The models developed for low fruit load conditions have shown higher RMSE, and MBE. Among them, the LW model had a slightly better performance than LN.

Table 5. Statistical indexes for validation test of the models for coffee leaf rust infection rate estimation, on the four different field conditions: HW = high fruit load, wide space; HN = high fruit load, narrow space; LW = low fruit load, wide space; and LN = low fruit load, narrow space. Dataset from Varginha, Carmo de Minas and Boa Esperança, all located in Minas Gerais, Brazil.

Field condition	RMSE (p.p.)	MBE (p.p.)	MAE (p.p.)	R^2
HN	13.40	0.08	8.40	0.810
LN	14.50	9.50	10.90	0.729
HW	12.40	-1.40	8.90	0.820
LW	14.45	-2.07	8.32	0.828

RMSE: root mean square error (p.p.); MBE: mean bias error (p.p.); MAE: mean absolute error (p.p.); R^2: coefficient of determination.

The HN model has the lowest False Negative occurrences (Table 6), as a result, is more accurate. A model with reduced False Negative frequency is more conservative (Duttweiler et al. 2008), due to False Negative means a non-spray whilst it is necessary. On field False Negative will result on disease progress, while the objective of using a forecast is to keep disease intensity under low values. The disease intensity under lower values has a key hole on keeping the epidemic under control during the season, as shown by Kushalappa and Chaves (1980), in which the major importance variable on CLR progress was the percent spore area index. Therefore, low inoculum source tends to result on low disease progress.

Due to aforementioned lower errors and higher accuracy of HN model, this model was chosen as the best between the four proposed on this research for CLR infection rate estimation. Having only one model simplifies the CLR estimation, avoiding running different models (with different inputs). Moreover, does not require constant communication with growers about their field conditions. As easier the model language, interpretation, and less growers' information are required, as accessible is the model application at field scale (Gillespie et al. 1993; Gleason et al. 1995; Magarey and Isard 2017).

Table 6. Contingency table of the coffee rust infection rate estimation models' validation assessments, on the four different field conditions: HW = high fruit load, wide space; HN = high fruit load, narrow space; LW = low fruit load, wide space; and LN = low fruit load, narrow space. Dataset from Varginha, Carmo de Minas and Boa Esperança, all located in Minas Gerais, Brazil.

Models	Threshold to 5 p.p. (%)	10 p.p. (%)
HN (n = 44 months)		
True Negative	29.55	36.36
False Positive	20.45	22.73
True Positive	45.45	36.36
False Negative	4.55	4.55
LN (n = 44)		
True Negative	20.45	38.64
False Positive	47.73	45.45
True Positive	25.00	15.91
False Negative	6.82	0.00
HW (n = 63)		
True Negative	26.98	44.44
False Positive	19.05	17.46
True Positive	44.44	23.81
False Negative	9.52	14.29
LW (n = 63)		
True Negative	49.21	68.25
False Positive	12.70	3.17
True Positive	14.29	1.59
False Negative	23.81	25.40

* Thresholds of 5 and 10 percental points (p.p.) were chosen based on Zambolim et al. (1997) and Kushalappa et al. (1984), respectively, to use as risk limit on CLR control, also used on Meira, Rodrigues, and Moraes (2009) to model performance assessment.

As HN model was chosen for CLR infection rate estimation, on Tables 7 and 8 are presented the model performance on high and low fruit load field conditions, disregarding row spacing. These are the situations in which the model is expected to work, on fields. The MAE of 8.60 p.p. for high load and 9.50 for low load (Table 7) and small percentages of False Negatives (Table 8), show the good performance of the model on different field conditions than those in which it has been developed. The coefficient of determination is also high, of 0.839, and 0.785 for high and low fruit loads, respectively.

There are small percentages of errors due to possible no sprays (False Negative) for the model on both situations (low and high loads). The higher threshold is less conservative, while the lower threshold is a more conservative situation (Duttweiler et al. 2008). As for CLR the residual period of the fungicides is of 60 to 90 days, the possibility of a lack of control decrease. It occurs as a consequence of one spray made on a month followed by a

False Negative estimation, will result on a spray not made, however is still on the residual period.

Table 7. Statistical indexes for validation test of the HN model for coffee leaf rust infection rate estimation, on the two possible field conditions, due to yield alternancy. High = high fruit load; Low = low fruit load field conditions. Dataset from Varginha, Carmo de Minas and Boa Esperança, all located in Minas Gerais, Brazil. HN = high fruit load, narrow space.

Field condition	RMSE (p.p.)	MBE (p.p.)	MAE (p.p.)	R^2
High	12.70	0.30	8.60	0.839
Low	14.20	5.30	9.50	0.785

RMSE: root mean square error (p.p.); MBE: mean bias error (p.p.); MAE: mean absolute error (p.p.); R^2: coefficient of determination.

Meira, Rodrigues, and Moraes (2008) reached an accuracy of 73% forecasting CLR infection rates, with 79% of the events of more than 5 p.p. increase correctly estimated. They found as more important weather-variables, the temperature during leaf wetness periods, expected yield, mean of maximum temperatures during the incubation period, and relative humidity. Using the HN model from the present model, we obtained 73.83% of accuracy for 5 p.p., similar to the results from Meira, Rodrigues, and Moraes 2008).

Table 8. Contingency table of the HN model for coffee rust infection rate estimation, on the two fruit loads conditions, due to yield alternancy. High = high fruit load; Low = low fruit load field conditions. Dataset from Varginha, Carmo de Minas and Boa Esperança, all located in Minas Gerais, Brazil.

Fruit load conditions	Threshold	
	5 p.p. (%)	10 p.p. (%)
High (n = 107 months)		
True Negative	27.10	39.25
False Positive	19.63	21.50
True Positive	46.73	29.91
False Negative	6.54	9.35
Low (n = 107)		
True Negative	26.17	42.06
False Positive	38.32	35.51
True Positive	29.91	17.76
False Negative	5.61	4.67

* Thresholds of 5 and 10 percental points (p.p.) were chosen based on Zambolim et al. (1997) and Kushalappa et al. (1984), respectively, to use as risk limit on CLR control, also used on Meira, Rodrigues, and Moraes (2009) to model performance assessment.

For both high and low fruit loads the HN model presented the same trend (Figure 5), of overestimation on lower disease intensity, and the opposite occurring on the high levels.

For high fruit loads, the trend line crosses the 1:1 line around 40% of disease intensity, while on low fruit load it happens at around 70% of incidence. There is a clear difference between the incidence levels of high and low fruit loads. High fruit load conditions have several observations ranging from zero to 100%, while low has the data concentrated up to 60%, with some observations above this intensity.

The HN model resulted on high R^2 on the estimation for both fruit load conditions, as seen on all analysis between high and low fruit loads. However, for low fruit load conditions the HN model had the lowest performance, with accuracy of 56.08% and on 59.82%, on 5 and p.p., respectively. As low fruit loads are not the focus of the growers, and several farms are using the ‘zero season’ the application of the model on those situations will probably be very low.

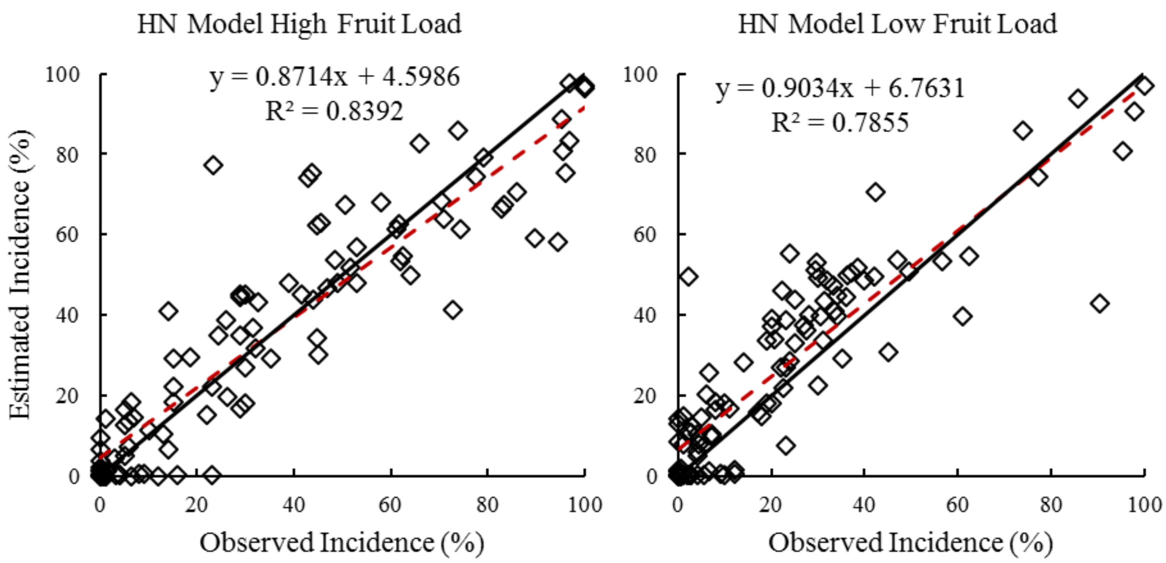

Figure 5. Performance of HN model on two possible fruit load conditions, due to yield alternancy. High = high fruit load; Low = low fruit load field conditions. Trend line (red dashed line) and 1:1 (straight line).

In addition to the environment, another important factor unapplied on the model, is the inoculum amount. It is an important vertex on the disease triangle (Bergamin Filho and Amorim 1996), however is not measured for CLR. In Brazil, this kind of measurement is not common, which could make, if required, this requirement a problem on the FS application. Even though, the model with more than 69% of accuracy, only weather-based can be a good tool to help growers in field CLR management, and can futurely be improved if inoculum measurements become a reality. Kushalappa et al. (1984) when developing a model for CLR infection rate prediction explained about the importance of inoculum playing an important role on the epidemic. For high fruit loads, the seasons in which the growers intend to have high incomes, the CLR control is pivotal. The FS shows a promisor use of the model, however field trials are essential to evaluate its performance under fungicide management situations.

2.4. Conclusions

The CLR has higher intensity values during high fruit load seasons. The Gompertz growth model was the best to describe CLR epidemics accurately. Monthly minimum air temperature and relative humidity are the main weather variables to estimate CLR apparent infection rate. Those variables are highly correlated to the temperature during high RH periods and to the length of this period, respectively. The model developed to estimate CLR apparent infection rate for HN conditions can also be used for other fields conditions (fruit load and rows space), with false negative occurrences below 10%, and accuracy above 73% on 5 p.p. threshold.

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3. PERFORMANCE OF A COFFEE LEAF RUST FORECAST MODEL TO RECOMMEND CHEMICAL CONTROL

ABSTRACT

Several phytosanitary problems occur on coffee farms in Brazil, affecting plant yield. Leaf miner (*Leucoptera coffeela*), nematodes, brown eye spot (*Cercospora coffeicola*), phoma leaf blight (*Phoma tarda*), and leaf rust (*Hemileia vastatrix*) are the most important. These pathogens affect as quality as quantity of coffee harvested. The coffee leaf rust (CLR) is the major disease threatening the fields, with the first report in Brazil in 1970. Chemical control is still essential for avoid damages on fields, and if not applied in the right time can result in large outbreaks. The disease triangle is composed by host, pathogen and weather, all pivotal on the CLR management. The weather favorability to disease infection is an important component of the epidemics management. Using a forecast system (FS), that considers weather role on CLR progress, this study aimed to assess a solely weather-based FS for timing sprays, in order to rationalize CLR control. In order to evaluate this CLR FS, two field trials were performed on 2015-16 (Varginha and Boa Esperança), and five during 2016-17 (Varginha, Boa Esperança, Uberlândia, Buritizal and Campinas). The FS estimates daily CLR infection rate, based on minimum air temperature and relative humidity measurements. These values, accumulate since the season beginning, returned cumulative infection rate (CIR). Foliar sprays timing in FS treatments were defined on more (MC) or less conservative (LC) thresholds, to compare with the regional traditional sprays. Treatments were: T1) without sprays; T2) regional traditional sprays; T3) FS MC, three sprays; T4) FS LC, three sprays; T5) FS LC, only two sprays; T6) same than T3, without the soil drench. A triazole fungicide was sprayed on soil (soil drench), during November, as the basis of CLR control, with exception of treatments T1 and T6. Popular fungicide, triazole plus strobilurin, was used on foliar sprays. Disease incidence was assessed, and area under disease progress curve (AUDPC) was calculated to treatments comparison. The Scott-Knott cluster analysis was done for compare AUDPC among treatments. The FS based treatments performed better than T2 in six of the seven trials, however without significant difference according to Scott-Knott cluster analysis procedure. Overall, treatments T4, and T3 kept the lowest AUDPC. The T5, also returned low AUDPC values, with only two fungicide sprays, becoming the most efficient for CLR control. The FS did not performed well on Campinas, presenting the necessity of regional thresholds calibration, once the FS is empirical based. The FS system performed better than traditional regional CLR management on the majority of the conditions.

Keywords: *Hemileia vastatrix*; Forecast system; Plant disease management

3.1. Introduction

Several phytosanitary problems threaten coffee plantations around the world. Among them, leaf miner (*Leucoptera coffeela*), nematodes, brown eye spot (*Cercospora coffeicola*), phoma leaf blight (*Phoma tarda*), and leaf rust (*Hemileia vastatrix* Berk. & Br.) are the most important, impacting coffee yield and quality (Guerreiro Filho 2006; Lima et al. 2010; Souza et al. 2011). The coffee leaf rust (CLR) is the main disease affecting coffee fields in Brazil (Brown et al. 1995; Boudrot et al. 2016).

During coffee growing seasons, CLR epidemics are mainly driven by weather conditions (Avelino et al. 2015). Fruit load also plays a major role in the disease intensity (Meira et al. 2009). As coffee is cultivated either under full sun or shaded, it becomes another influencing factor for CLR development once shading microclimate conditions are more conducive to this disease than under full sun. Shaded coffee system normally presents higher relative humidity and lower temperatures, conditions required by the leaf rust fungus to infect coffee leaves (López-Bravo et al. 2012). CLR has occurred in Brazil since its first appearance in 1970 (Schieber and Zentmeyer 1984), and despite advances for developing cultivars tolerant to this disease and for its controlling, it still causes damages where chemical control is not applied in the right time (Zambolim 2016).

As the disease triangle is composed by host, pathogen and climate, to know how weather conditions influence the disease epidemics can help to develop tools for improving control by better spray timing and/or by decreasing spray numbers, reducing the production costs and maximizing profits. Other benefits brought by rationalizing disease control is the reduction of chemical residues in the final product and in the environment.

The use of disease forecast systems (FS), based on weather-based spray timing rules, has been subject of several studies since 1990´s (Wallin 1962; Madden et al. 1978; Pitblado 1992; Garçon et al. 2004; Spolti et al. 2011; Rosli et al. 2017). These systems are the opposite of the calendar traditional control, which is based on the residual period of the fungicides on the leaves and the regional epidemics knowledge, meaning that this system does not take into account the climate effect on disease onset and development (Pitblado 1992).

Regardless of CLR intensity, coffee plants exhibit a biannual yield variation, according to its two-year phenology. Such characteristic is more evident in the plantations cultivated under full sun, like the majority of Brazilian farms. As a consequence of that, there is an alternation between a high yield (high fruit load) in one season followed by a low yield (low fruit load) in another, when the plants have less leaves (Camargo and Pereira 1994;

Avelino et al. 2015). Even considering that the CLR occurs in both years, its intensity will be higher when there is high fruit load, when coffee plants become more susceptible once beans are draining much of the photoassimilates, reducing the defenses of the plants against the disease (Kushalappa et al. 1983).

CLR control in the Brazilian coffee regions is mainly done with fungicides (de Souza et al. 2011), as most farms grow susceptible cultivars (Honorato Jr et al. 2015). The usual procedure is composed by a drench of triazol applied at the beginning of the rainy season, followed by one up to three foliar systemic sprays. This variation in foliar sprays number depends on disease intensity in the season (Kushalappa et al. 1984; Zambolim et al. 1997), which depends on the weather conditions and also on the grower economic condition.

Fungicides applied to control CLR are the same used for soybean rust (SBR); however, of ‘older generations’. Older generations mean that for SBR control modern fungicides with newer active ingredients (a.i.) have been released to overcome resistance problems, since the efficiency of old fungicides used till few seasons ago is decreased, mixing three or more a.i. in the same product (Godoy et al. 2011, 2017). Similar problem is also affecting CLR control; however, it is happening slower due to the longer CLR latent period, with more than 25 days (de Moraes et al. 1976), while SBR demands around 7 to 9 days (Melching et al. 1979). To avoid pathogen resistance, the use of fungicides should be rationalized through a FS, which means to spray only where and when required.

Considering the pivotal importance of weather conditions to CLR epidemic and the urgent need for reducing unnecessary sprays in the Brazilian coffee plantations, the hypothesis of this study is that a weather-based CLR forecast system could be useful for sprays recommendation in order to rationalize fungicide use in the Brazilian coffee production regions. According to that, the objective of the present study was to assess a CLR forecast system, based on minimum air temperature and average relative humidity, suitability to rationalize CLR management in several Brazilian locations.

3.2. Material and Methods

3.2.1. Coffee leaf rust forecast system

A CLR infection rate model, developed with disease incidence data observed in Mundo Novo and Catuaí cultivars of coffee plantation from three Procafé Foundation farms in Varginha (21º 34’ 00” S, 45º 24’ 22” W, 940 m), Carmo de Minas (22º 10’ 31” S, 45º 09’ 03”

W, 1180 m), and Boa Esperança (21º 03' 59" S, 45° 34'37" W, 830 m), all in Southern Minas Gerais, was used as the main reference for developing a CLR forecast system.

The best performance CLR infection rate estimation model (r_{HN}), developed in Chapter 1, requires as inputs the following weather variables: minimum air temperature (Tmin) and average relative humidity (RH), both on a daily basis, according to equation 3.1:

$$r_{HN} = -1.293 + 0.019\ Tmin_{(30\text{-}60d)} + 0.017\ RH_{(30\text{-}60d)} \qquad \text{(Equation 3.1)}$$

where: Tmin = minimum temperature average (ºC); RH = average relative humidity (%).

Thresholds were defined to recommend the sprays timing. The estimated daily infection rate was accumulated since 1 December, defining the cumulative infection rate (CIR). The thresholds of CIR for the consecutive sprays, considering more (MC) and less (LC) conservative decisions are presented in Table 1.

Table 1. Thresholds of cumulative infection rate (CIR) for each foliar spray to control coffee leaf rust. Estimated coffee leaf rust infection rate was accumulated since 1 December.

Spray	CIR Threshold
First	1.2
2^{nd} More Conservative (2^{nd} MC)	25.0
2^{nd} Less Conservative (2^{nd} LC)	35.0
3^{th} More Conservative (3^{rd} MC)	59.0
3^{th} Less Conservative (3^{rd} LC)	65.0

The thresholds for CIR were defined based on the following aspects: 1 - systemic triazol plus strobilurin are protective fungicides, which have a protective action, remaining on leaves before *Hemileia vastatrix* spore germination and infection (Schöfl and Zinkernagel 1997; Vincelli 2002); 2 - CLR incidence in the beginning of the season must be kept low, once high incidence in the beginning is likely to result in a poor disease control, allowing high incidence values in the end of the season, mainly because the fungicides use are protective, rather than curative; 3 - residual period of the fungicides are 60 days.

3.2.2. Field trials

Seven field trials were conducted to assess the CLR FS under field conditions. Two during the 2015-16 season and five during the 2016-17 season. The experimental sites covered three different regions (Figure 1): Varginha (21º 34’ 00” S, 45º 24’ 22” W, 940 m) and Boa Esperança (21º 03’ 59” S, 45° 34’37” W, 830 m), in Southern Minas Gerais; Uberlândia (18º 55’ 07” S, 48° 16’ 38” W, 863 m) in the Cerrado of Minas Gerais, western part of the state, and Buritizal (20º 11’ 28” S, 47° 42’ 30” W, 855 m), in the north of São Paulo, border with Minas Gerais; and Campinas (22º 54’ 20” S, 47° 03’ 39” W, 854 m). The first four locations are in traditional coffee regions, whereas Campinas is in a region intensively cultivated with sugarcane.

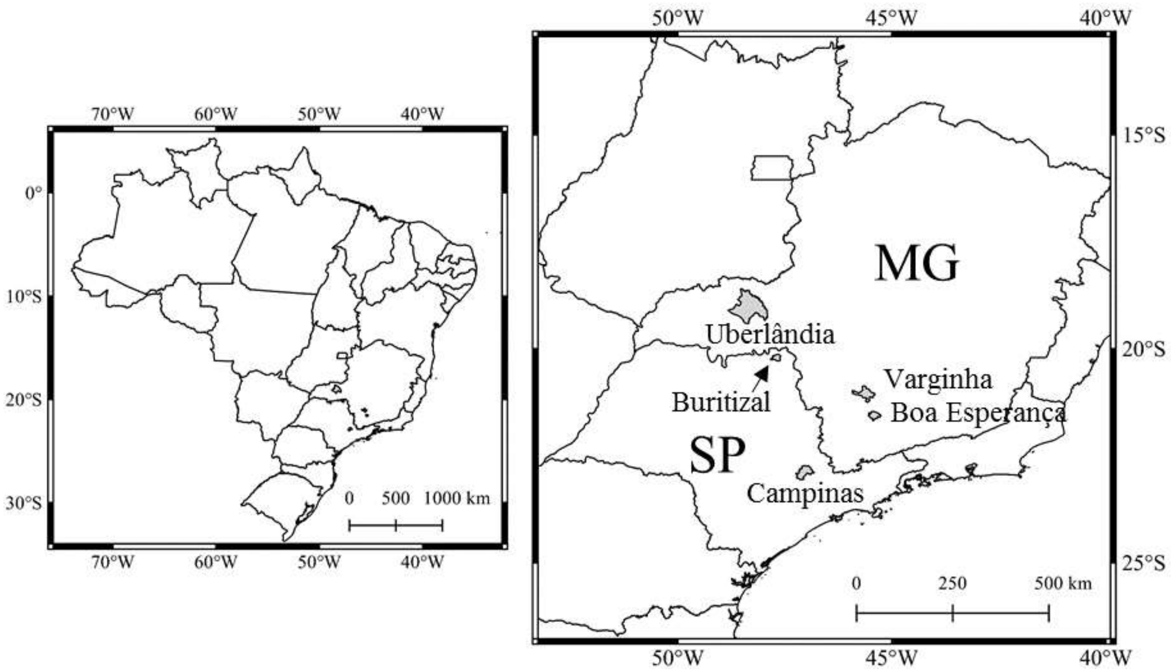

Figure 1. Field trials locations used for assessing the coffee leaf rust forecast system: 2015-16 season - Varginha and Boa Esperança; 2016-17 season - Varginha, Boa Esperança, Buritizal, Uberlândia, and Campinas. States of São Paulo (SP) and Minas Gerais (MG).

The plots were distributed in a randomized blocks design, with three, four or six repetitions, and six treatments. In the 2015-16 season, fewer repetitions were planned, which increased in the 2016-17 season. In Varginha, four repetitions were made during the 2015-16 season, while in Boa Esperança, three. In the 2016-17 season, all field trials were performed with six blocks. The blocks were distributed into the coffee plantation rows in which a row was a block and the treatments were randomly distributed. All field trials were performed in adult coffee fields.

The area under disease progress curves (AUDPC), was calculated as the measure to compare treatments (Shaner and Finney 1977). The incidence assessments were conducted according to Chalfoun (1997), where at least 100 leaves of the 3rd or 4th knot of middle branches were assessed per plot, in a non-destructive sampling. The assumptions of residues normality (Shapiro-Wilk test) and variances homogeneity were checked. For Varginha (2015-16 season) and Boa Esperança (2016-17 season) the data transformation using root square was applied, while for Uberlândia the cube root was necessary to reach the assumptions of the Scott-Knott procedure, which was applied for variance analysis and comparisons among treatments (Scott and Knott 1974).

Six treatments were conducted in the field trials, as follows: T1 (control) - without fungicide sprays; T2 (traditional) - planned according to traditional management in the region (two or three sprays of systemic fungicide); T3 (FS More Conservative) - using more conservative thresholds for 2nd and 3th sprays (Table 1), planned for three sprays in each location; T4 (FS Less Conservative) - using less conservative thresholds for 2nd and 3th sprays (Table 1), planned for three sprays in each location; T5 (FS, only two sprays) - the 2nd spray considered the less conservative threshold; T6 (FS More Conservative, without drench) - in the same protocol of T3, however, without soil drench.

Soil drench is the first fungicide application for CLR control in the season and is a mix of triazole (cyproconazole) and neonicotinoid (thiamethoxan, an insecticide for leaf miner control). The applied dose was 1 kg diluted in 200 L of water and 0.05 L was sprayed on each plant side, close to the stem. The foliar fungicide spray was triazole (cyproconazole) plus strobilurin (azoxystrobin), as most growers use (Honorato Jr et al. 2015) at recommended doses of 0.5 L diluted in 400 L per hectare for sprays. The soil drench is usually applied in November, when the soil water is high. This drench was applied for treatments T2, T3, T4, and T5.

Automatic weather stations were installed in the farms of Varginha and Boa Esperança. For Uberlândia and Buritizal, weather data were obtained from the closest National Institute of Meteorology (INMET) weather station (for Buritizal, data from Ituverava, SP, were used); however, not inside the farm. For Campinas, data were obtained from Agritempo/EMBRAPA network.

3.3. Results and Discussion

3.3.1. Sprays timing

The first sprays always happened before 16th December, according to the weather conditions (Figure 2), acting as a protective fungicide. The first spray is highly important due to the protective mode of action of fungicides. Strobilurin present excellent performance as preventive fungicide, killing germinated spores; however, it shows poor performance when infection is already established (Wong and Wilcox 2001; Vincelli 2002). Triazoles also present better performance for killing on germ tubes, without activity after leaf damage (Schöfl and Zinkernagel 1997). Triazoles fungicides belongs to the sterol biosynthesis inhibitors group, with effect on the sterol biosynthesis, started from 6-8h after germination (Pontzen and Scheinpflug 1989). Therefore, there is only one threshold for the first spray in order to protect leaves of infection, keeping low incidence values at the epidemic onset.

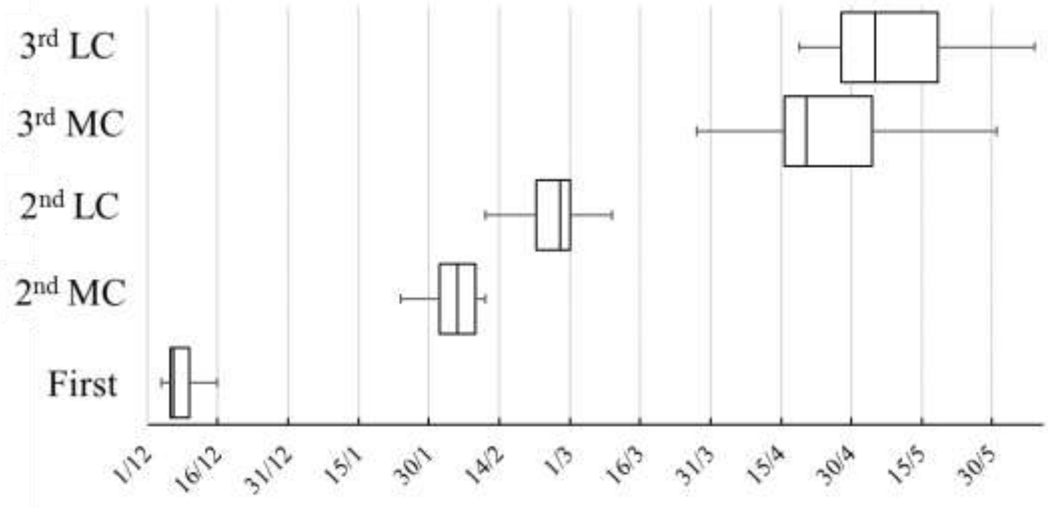

Figure 2. Dates (day/month) when each threshold were expected to be reached for recommending the different foliar sprays for coffee leaf rust control during the field experiments in Varginha, Boa Esperança and Uberlândia, MG, and Buritizal and Campinas, SP, Brazil. First: first foliar spray; MC: more conservative; and LC: less conservative thresholds.

As the residual period of fungicides commonly used for CLR control is 60 days, the difference between thresholds from first to second and second to third sprays were arbitrarily defined for the cumulated infection rates (CIR) that returns a length around this period. The 2nd MC spray was scheduled until 12 February, around 60 days after the first one. The 2nd LC happened from 11 February to 9 March, intending to keep the plants protected during a longer period, as demonstrated mainly in T5. The 3rd MC is around 60 days after the 2nd MC. The chemical control presented here aimed to reduce CLR infection rate, resulting in a lower disease incidence at the end of the season (Kushalappa 1989a). Also, the 2nd LC threshold was planned with the objective of reducing one spray. In cases of high weather favorability, by infection rates estimation, this spray tends to be near the last moment of the 2nd MC, avoiding lacks of control. Besides, when the weather is less favorable, the tendency was a late spray, covering a larger part of the season, with only two sprays.

3.3.2. Field trials

CLR reached the highest AUDPC values in Buritizal (11017.2), Uberlândia (8557.8), and Campinas (8272.1), respectively. In Varginha, the two years of experiments resulted in similar AUDPC values (4649.0 and 4741.4). In Boa Esperança, 2015-16 season reached higher AUDPC (3019.3) than observed in 2016-17 season (1821.6). The control treatment showed the importance of the fungicides to keep CLR under low incidence values in all sites (Figures 3 to 10).

In Varginha, over the 2015-16 season (Figure 3), the highest progress rate was observed after the assessment in January, reaching the maximum of 52% of symptomatic leaves at the end of May (Figure 3). The treatments T2, T4 and T5 finished the evaluation period with very low incidence values, respectively 7.5%, 1.5% and 4.5%. The highest disease values were observed in T3 (21%) and T6 (19.5%). As the disease showed a high progress rate in the beginning of March and the second spray in these treatments (T3 and T6) occurred one month earlier, possibly the amount of fungicide on leaves was not enough to keep the disease under control with high inoculum pressure and favorable weather.

According to AUDPC, the best performance for CLR control was observed in T4, T2 and T5 (Figure 3); however, without differences between them by Scott-Knott test. T3 and T6 were less effective to control CLR. As T5 had one spray less, without significant difference in relation to T4 and T2, was considered the most effective treatment for 2015-16 season in Varginha. By comparing T3 and T6, there was no benefit by applying the soil drench during this season, since the AUDPC was the same with or without this procedure.

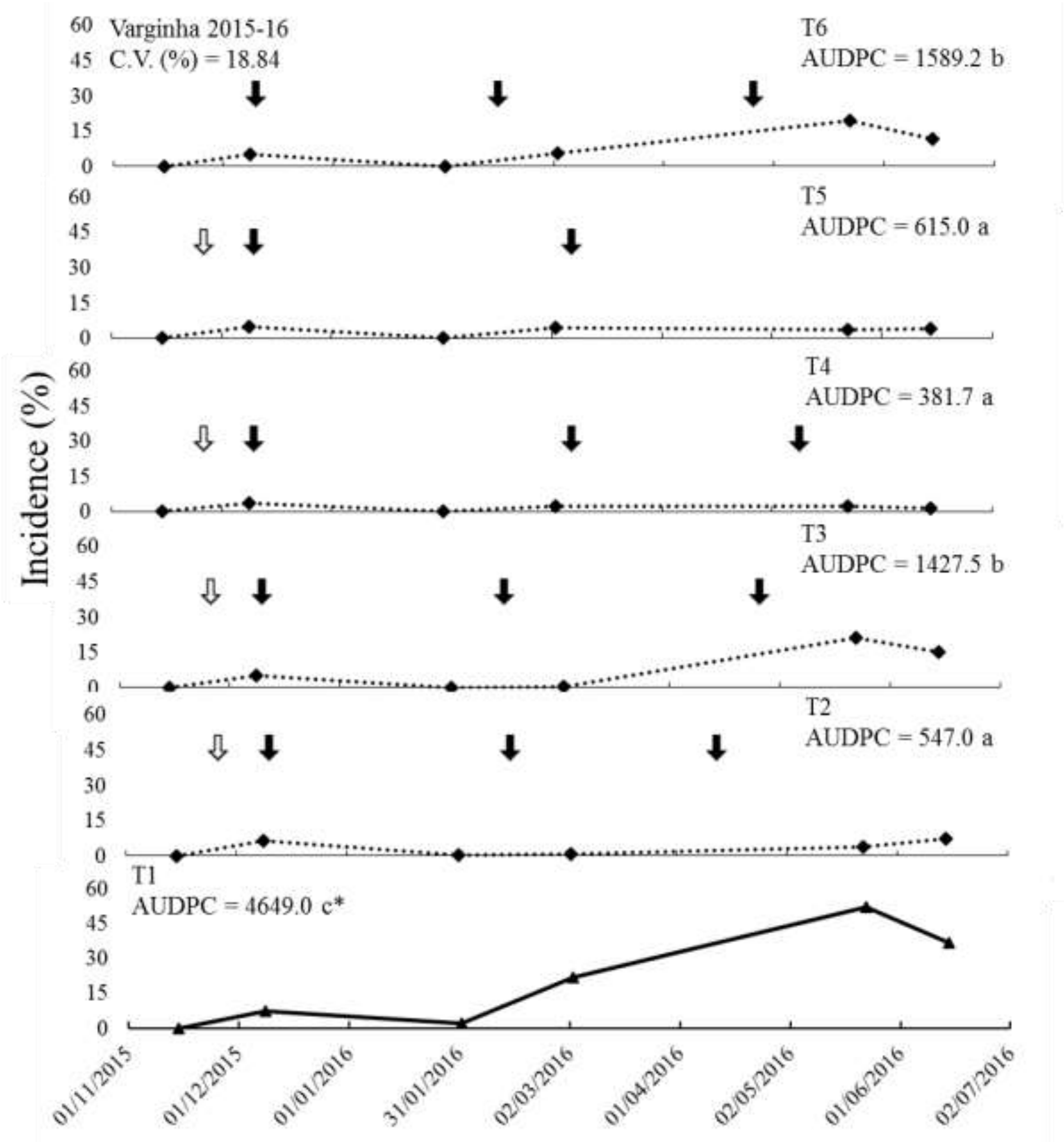

Figure 3. Coffee rust progress curves during the field trial for assessing the coffee leaf rust forecast system in Varginha, MG, Brazil, during the 2015-16 season. White filled arrows mean soil drench fungicide (triazole). Black filled arrows mean leaf fungicide sprays (triazole + strobilurin). Dots are incidence assessment dates. AUDPC = area under disease progress curve. *Values followed by the same letter are not significantly different at α = 0.05 according to the Scott-Knott cluster analysis procedure.

In Boa Esperança, in the 2015-16 season (Figure 4), the control treatment presented a maximum number of leaves with lesions of 30.7% (Figure 4). CLR was under low incidence values until the assessment conducted at the beginning of February, similar to what was observed in Varginha in the same season. The sequence from the lowest to the highest AUDPC was: T3, T4, T2, T5, and T6. However, no significant differences were observed among them, according to the Scott-Knot test. The treatment with two sprays (T5) was the most effective, since it saves one fungicide spray, which reduces the costs. T3 and T6 had similar effects for the disease control, showing no difference for the use or not of the soil spray.

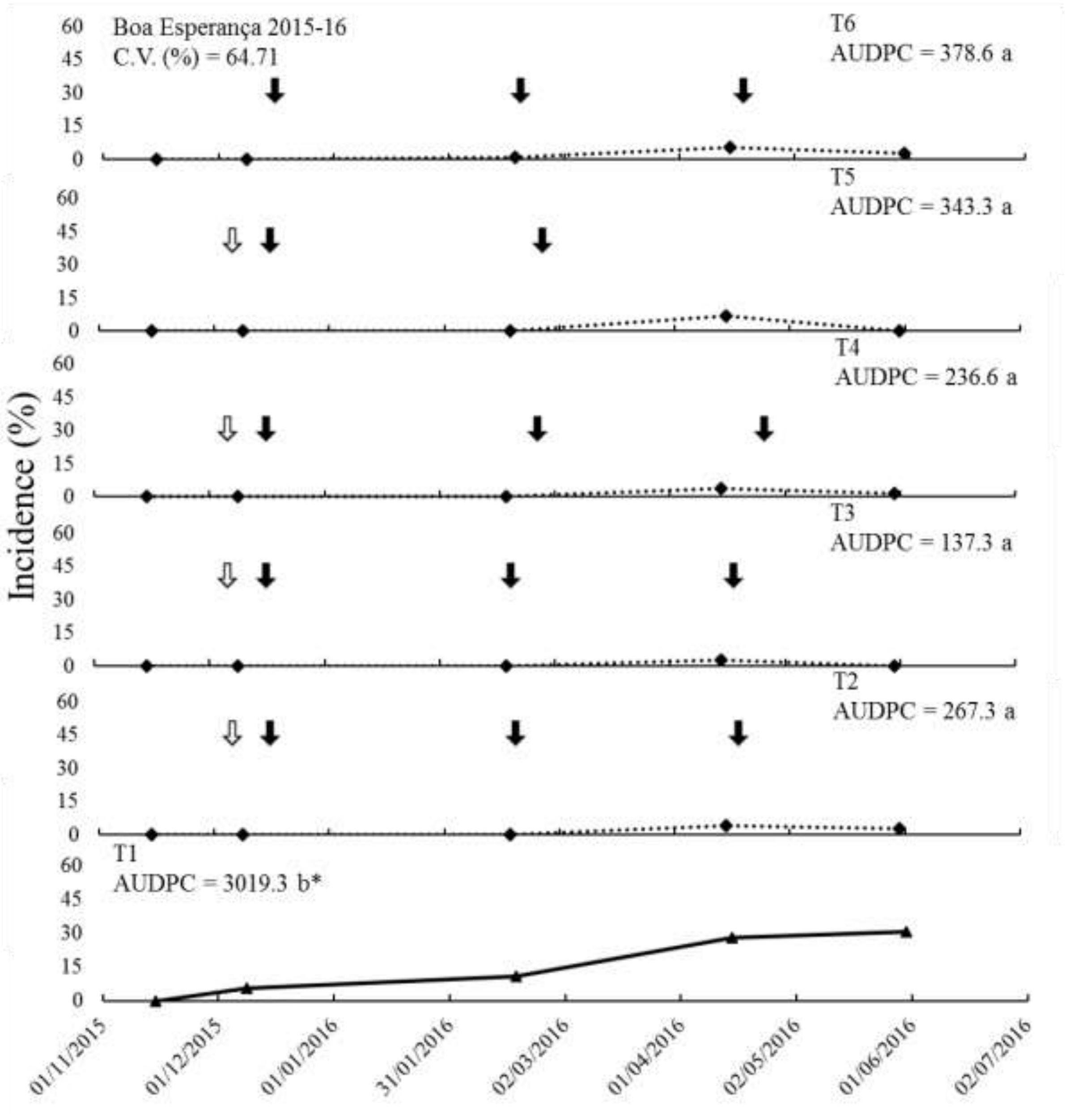

Figure 4. Coffee rust progress curves during the field trial for assessing the coffee leaf rust forecast system in Boa Esperança, MG, Brazil, during the 2015-16 season. White filled arrows mean soil drench fungicide (triazole). Black filled arrows mean leaf fungicide sprays (triazole + strobilurin). Dots are incidence assessment dates. AUDPC = area under disease progress curves. *Values followed by the same letter are not significantly different at α = 0.05 according to the Scott-Knott cluster analysis procedure.

In Varginha, the CLR epidemic in 2015-16 (Figure 3) and 2016-17 (Figure 5) seasons followed the same pattern with a higher CLR progress rate in February. This similar CLR occurrence was justified by the weather conditions in these two seasons, respectively: RH of 83.8% and 83.3%; Tmin of 17.5 ºC and 17 ºC (Figure 10).

In all treatments with fungicide spray plots the incidence was lower than control plots, keeping incidence lower than 10% until the end of the season. AUDPC was lower in T3, followed by T4, T2, T5 and T6, but with no difference among them according to the Scott-Knott test. CLR control was more effective in T5, which required only two fungicide sprays.

Boa Esperança, during the 2016-17 season (Figure 6), presented the lowest AUDPC for all control treatments (T1). This behavior was caused by the late disease development (Figure 6), which was promoted by the unfavorable weather conditions, with less rainfall and, consequently, lower relative humidity (Figure 10). The maximum incidence in T1 was observed in the last assessment in late June (39.2%). All fungicide plots had low disease incidence levels until the end of the assessments period. AUDPC, from lower to higher, was: T6, T4, T5, T2, and T3, without any difference among them, according to the Scott-Knott test.

In Uberlândia in the 2016-17 season (Figure 7), CLR reached high incidence, with 80% on 23 May and 100% on 14 June. The probable main cause for that were the rainfall events (Figure 10), promoting mainly disease dispersion. In all sprayed treatments, the disease control was efficient, keeping incidence below 25% over the assessment period. The AUDPC crescent sequence was: T4, T3, T5, T6, and T2. In this site-season, the advantage of FS timing fungicide spray is clearer, due to the higher AUDPC for T2; however, no difference was observed among them. Treatments T3 and T6, which differ only in the soil drench application, did not differed from each other, although T3 kept lower CLR incidence until the season end. The forecast system did not reach the threshold for a 3rd spray in any treatment. In this region (Minas Gerais Cerrado), the management with two sprays is more common than in Varginha and Boa Esperança (Southern Minas Gerais), where three sprays are commonly required (Figures 3 to 6)

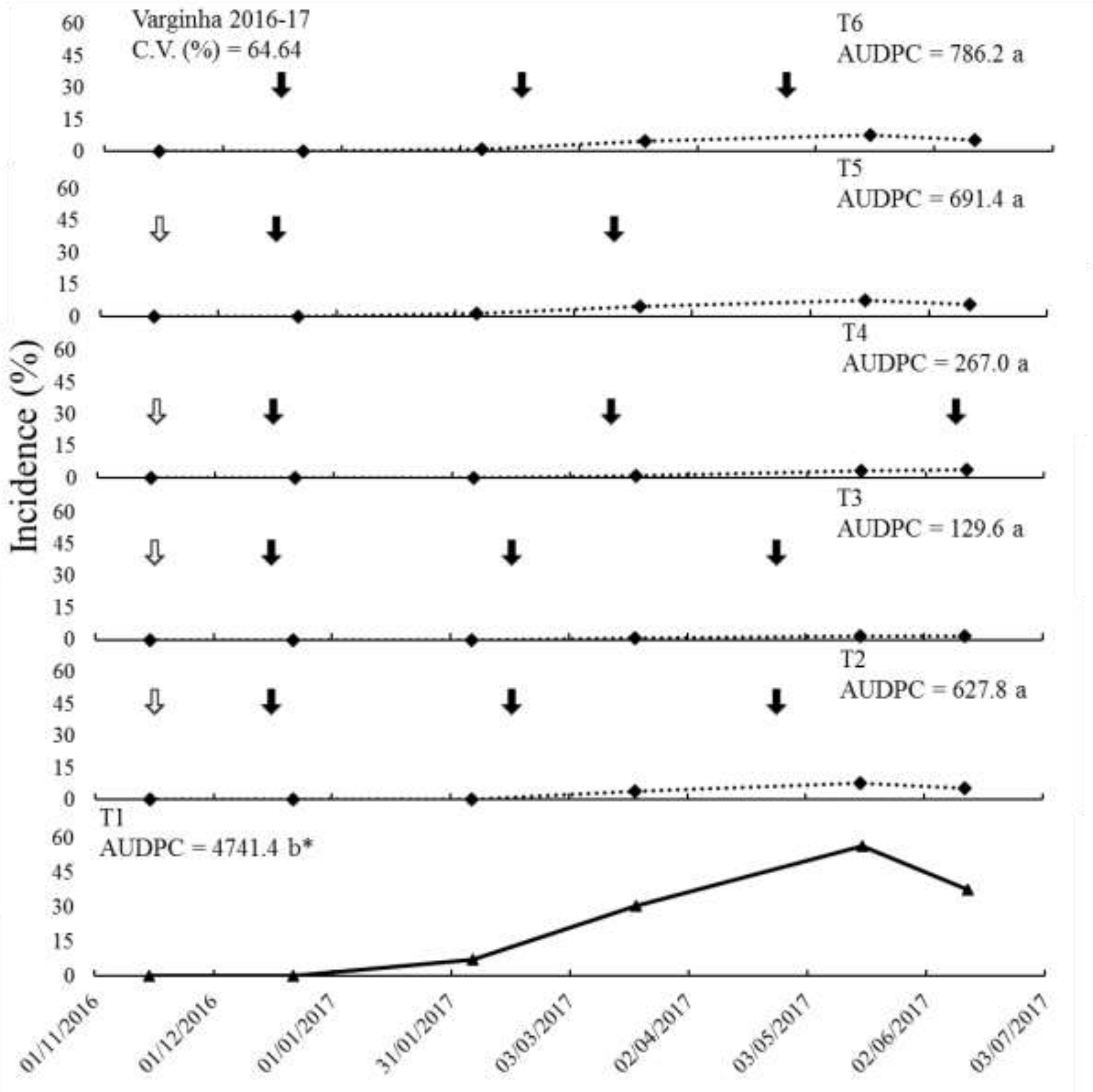

Figure 5. Coffee rust progress curves during the field trial for assessing the coffee leaf rust forecast system in Varginha, MG, Brazil, during the 2016-17 season. White filled arrows mean soil drench fungicide (triazole). Black filled arrows mean leaf fungicide sprays (triazole + strobilurin). Dots are incidence assessment dates. AUDPC = area under disease progress curves. *Values followed by the same letter are not significantly different at $\alpha = 0.05$ according to the Scott-Knott cluster analysis procedure.

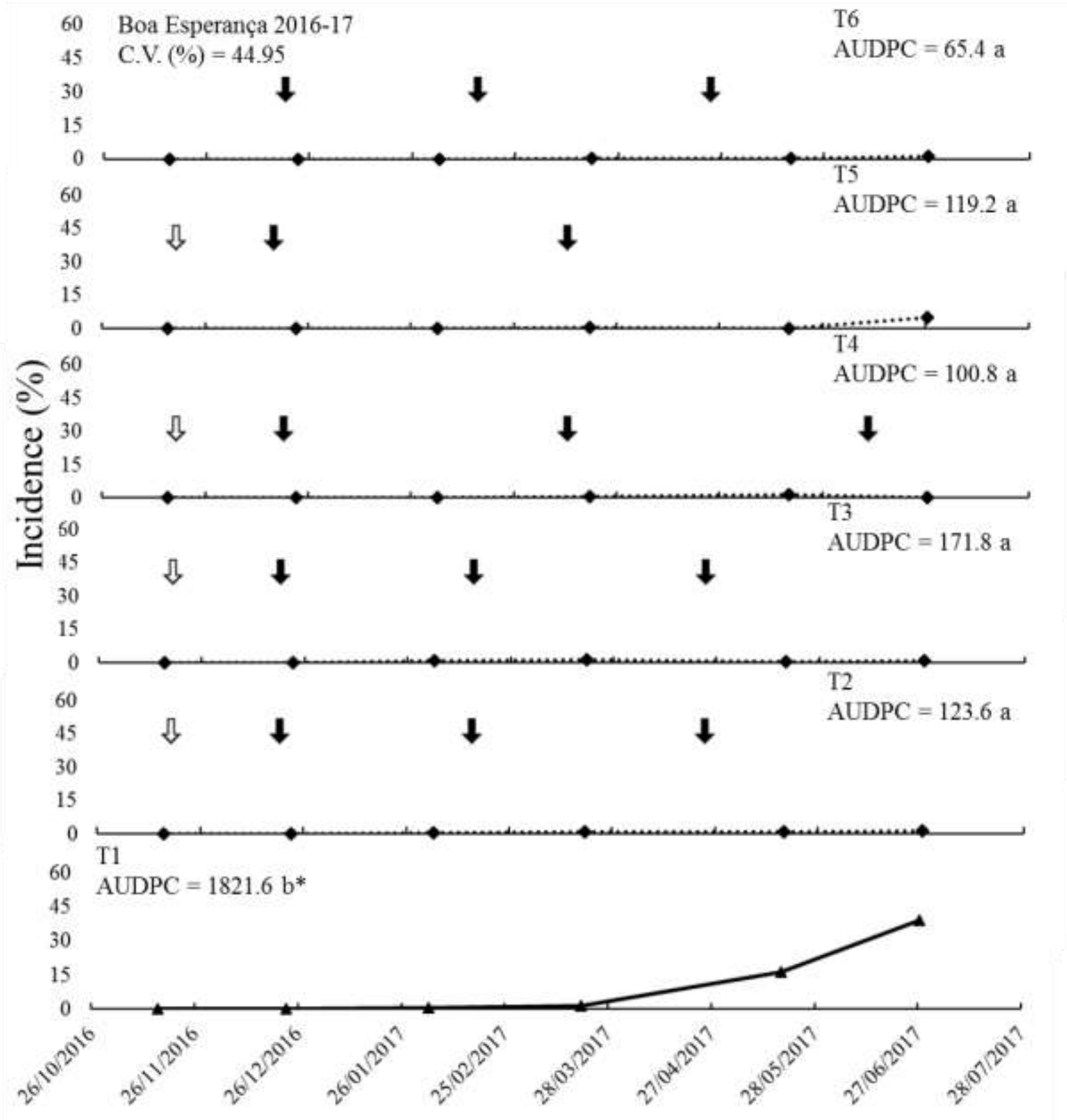

Figure 6. Coffee rust progress curves during the field trial for assessing the coffee leaf rust forecast system in Boa Esperança, MG, Brazil, during the 2016-17 season. White filled arrows mean soil drench fungicide (triazole). Black filled arrows mean leaf fungicide sprays (triazole + strobilurin). Dots are incidence assessment dates. AUDPC = area under disease progress curves. *Values followed by the same letter are not significantly different at $\alpha = 0.05$ according to the Scott-Knott cluster analysis procedure.

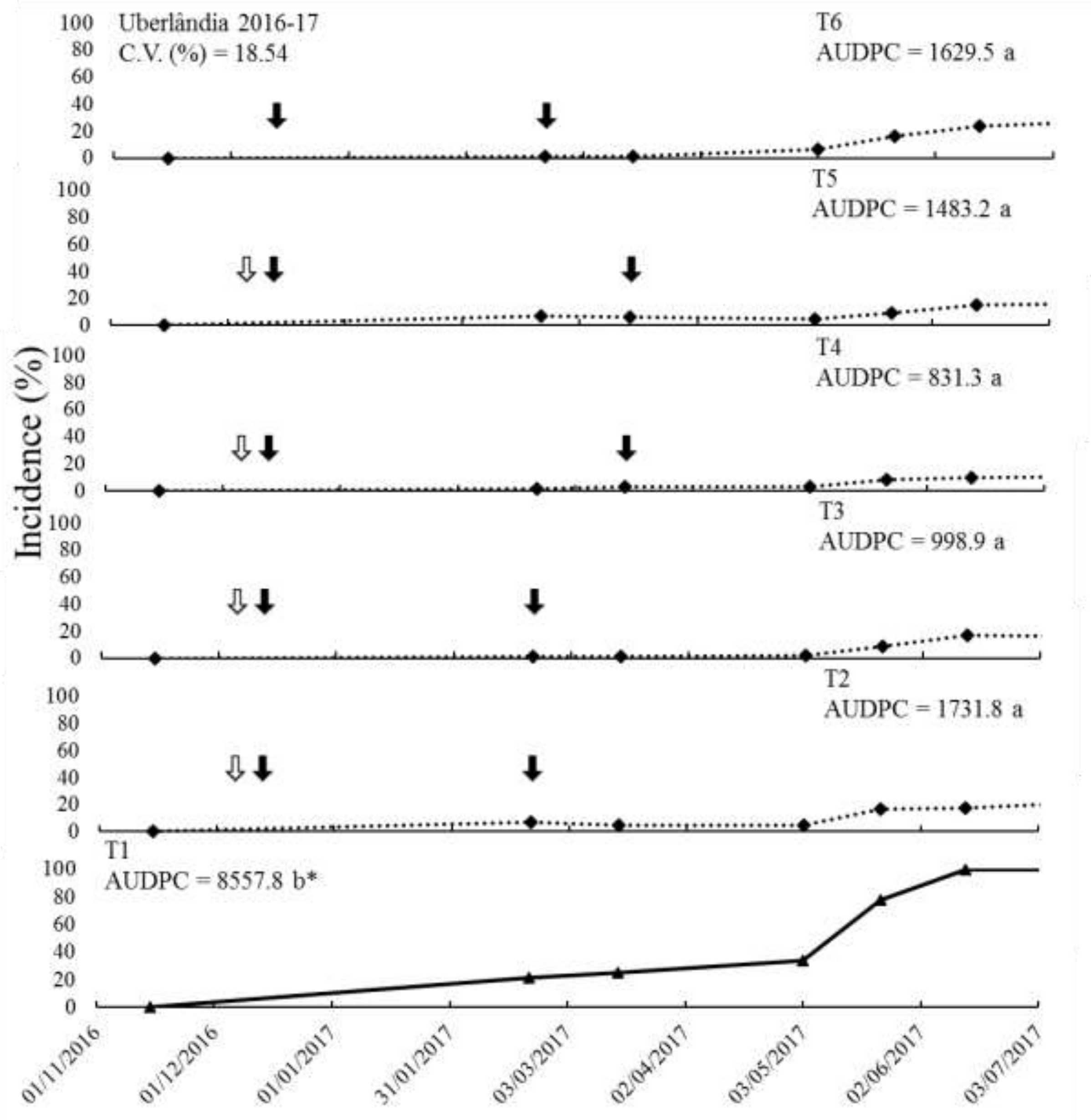

Figure 7. Coffee rust progress curves during the field trial for assessing the coffee leaf rust forecast system in Uberlândia, MG, Brazil, during the 2016-17 season. White filled arrows mean soil drench fungicide (triazole). Black filled arrows mean leaf fungicide sprays (triazole + strobilurin). Dots are incidence assessment dates. AUDPC = area under disease progress curves. *Values followed by the same letter are not significantly different at $\alpha = 0.05$ according to the Scott-Knott cluster analysis procedure.

In Buritizal, during the 2016-17 season (Figure 8), CLR incidence reached high levels, similar to Uberlândia, showing all leaves with symptoms, with intense CLR evolution from February onwards. The best control was obtained with T3 and T4, followed by T6, T2 and T5 presented similar performance, which evidenced the importance of the third spray to keep CLR controlled.

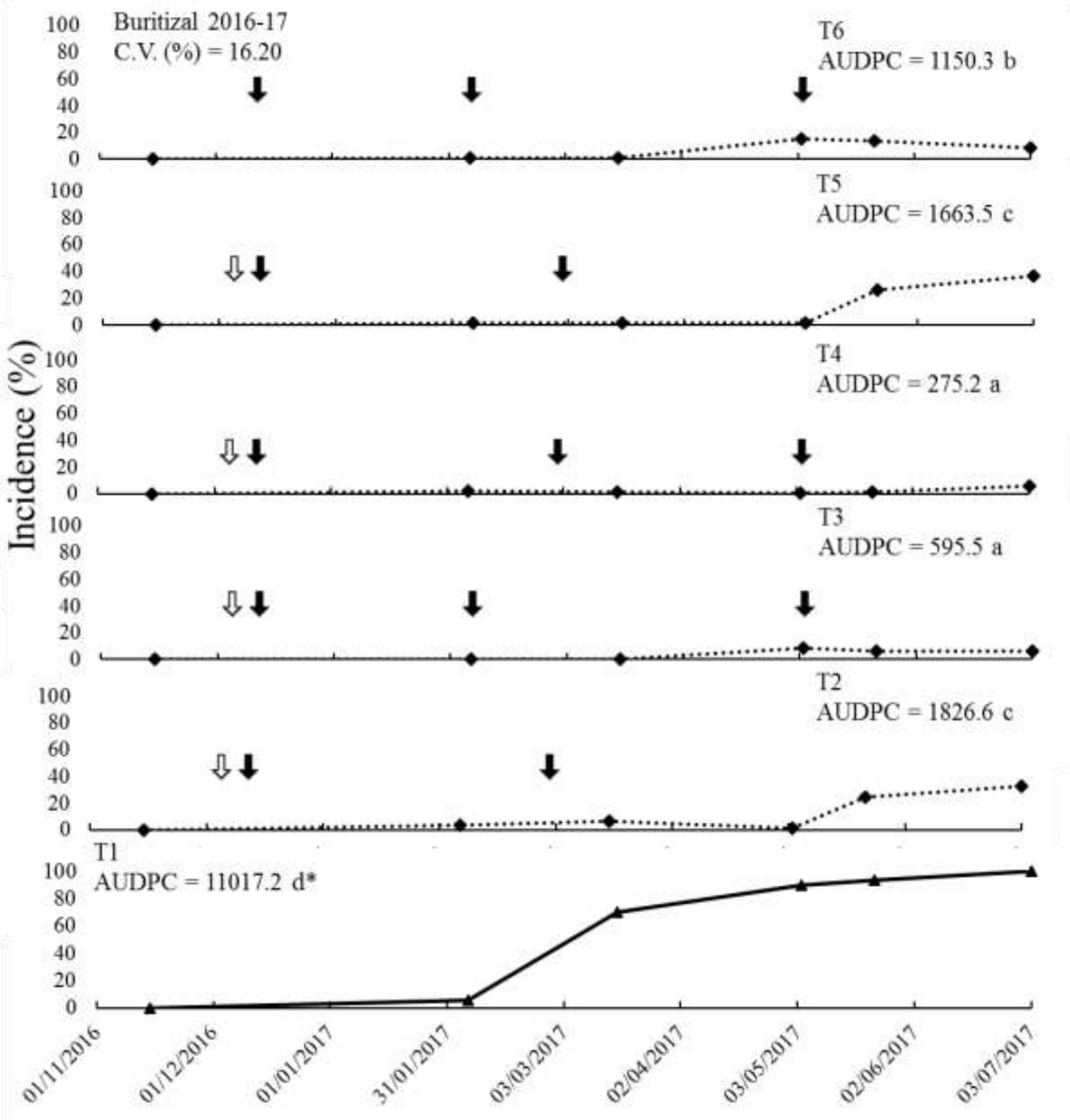

Figure 8. Coffee rust progress curves during the field trial for assessing the coffee leaf rust forecast system in Buritizal, SP, Brazil, during the 2016-17 season. White filled arrows mean soil drench fungicide (triazole). Black filled arrows mean leaf fungicide sprays (triazole + strobilurin). Dots are incidence assessment dates. AUDPC = area under disease progress curves. *Values followed by the same letter are not significantly different at $\alpha = 0.05$ according to the Scott-Knott cluster analysis procedure.

In Campinas, the FS recommended a maximum of two sprays, according to the thresholds defined. The control treatment presented a CLR incidence level of 40% in the first evaluation in February (Figure 9). This is the highest incidence level for this date, in comparison to the other sites. The maximum incidence was 71% in June. The sprays of the treatment T2 showed the best disease control, since it was the only one to recommend the third spray. As a function of that, this was the only location to present T2 as the best system for controlling CLR, differing substantially from the other treatments according to Scott-Knott test (α = 0.05). The other treatments did not differ among them. This was the only location where the CLR FS was worst than T2.

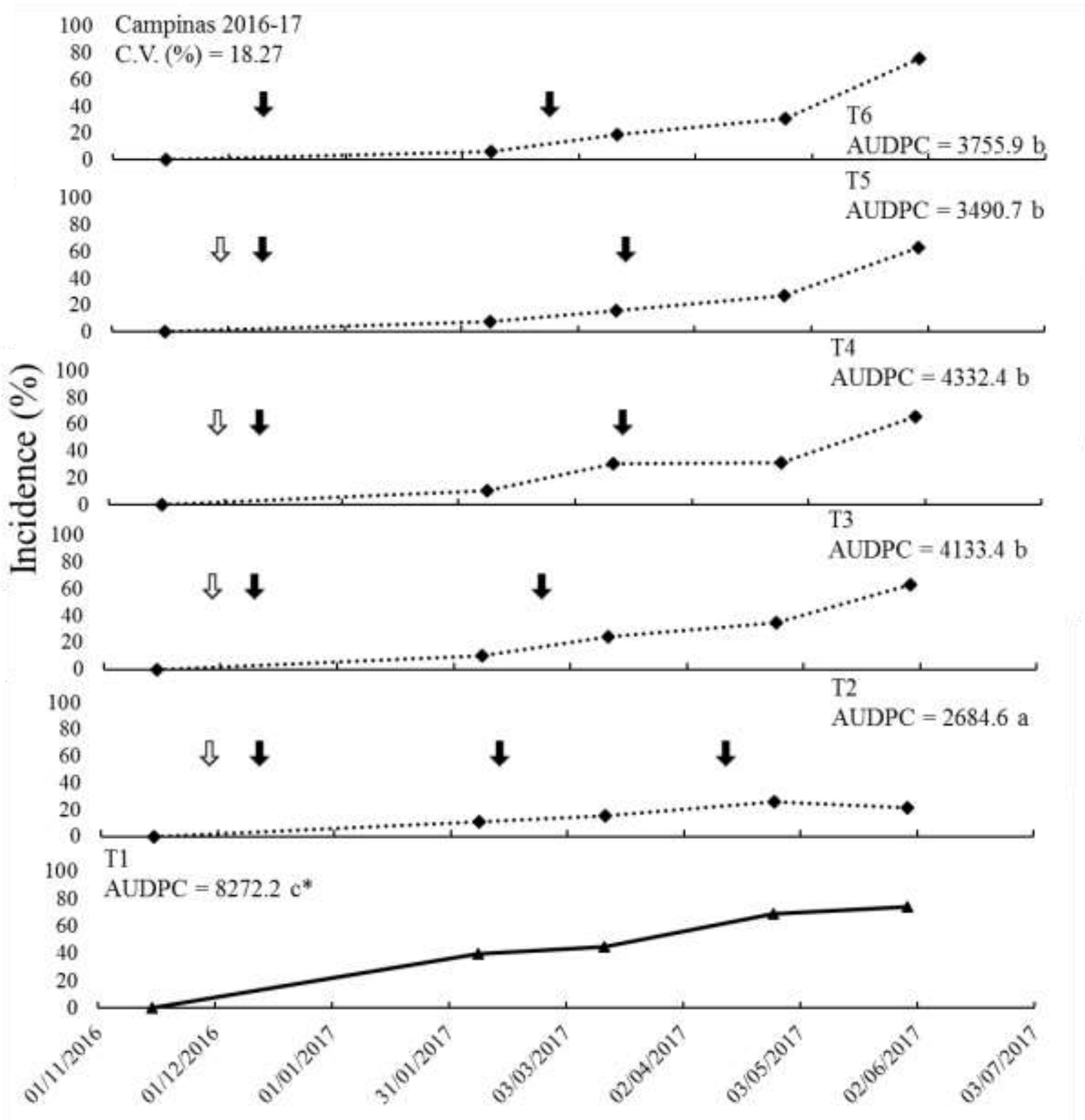

Figure 9. Coffee rust progress curves during the field trial for assessing the coffee leaf rust forecast system in Campinas, SP, Brazil, during the 2016-17 season. White filled arrows mean soil drench fungicide (triazole). Black filled arrows mean leaf fungicide sprays (triazole + strobilurin). Dots are incidence assessment dates. AUDPC = area under disease progress curves. *Values followed by the same letter are not significantly different at α = 0.05 according to the Scott-Knott cluster analysis procedure.

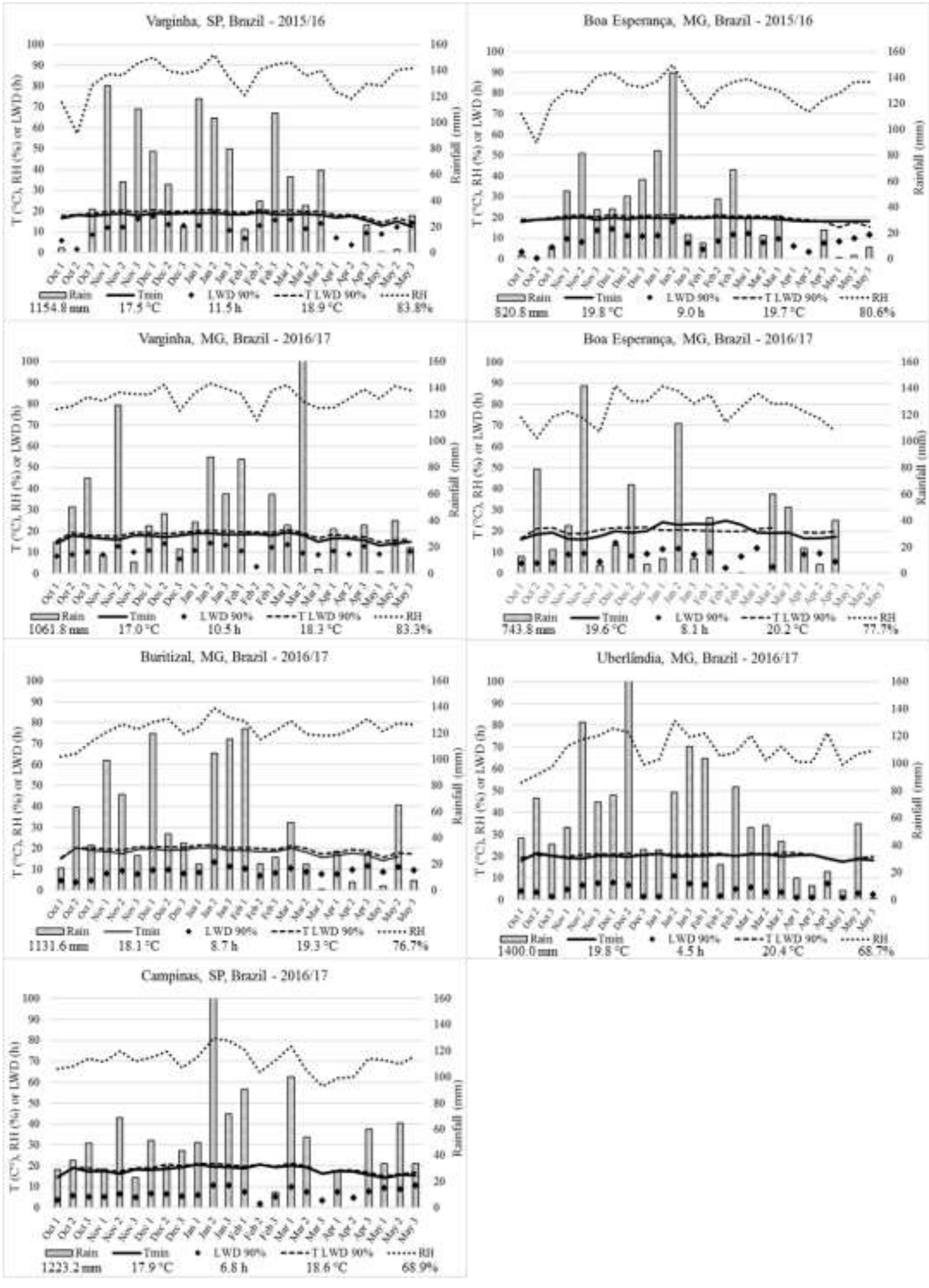

Figure 10. Weather variables for each 10-day period in the experimental sites where field trials were conducted for assessing the coffee leaf rust infection rate forecast system: Varginha, Boa Esperança and Uberlândia, Minas Gerais (MG); and Buritizal and Campinas, São Paulo (SP), Brazil. Rain = Rainfall (mm); Tmed = average temperature (ºC); LWD 90% = hours of leaf wetness duration estimated when RH is equal to or above 90% (h); T LWD 90% = temperature during the LWD 90% hours (ºC); RH = average relative humidity (%). As hourly data were not available for Campinas, they were interpolated based on the closest (Itapira and Sorocaba, SP) weather stations, in order to determine LWD 90% and T LWD 90%.

The rankings of treatments with better performance in the field trials are shown in Table 2. T4 presented the best control in three experiments (Varginha, 2015-16, Uberlândia, and Buritizal, 2016-17), whereas T3 was the best in two (Boa Esperança, 2015-16, and Varginha, 2016-17), T6 in one (Boa Esperança, 2016-17) and T2 in one (Campinas, 2016-17). T4 had the second-best performance in three site-seasons, whereas T5 was the second in Campinas. The poor performance of the CLR FS in Campinas can have two main reasons: the quality of weather data, since FS depends basically on air temperature and relative humidity; or the necessity of thresholds adjustments, once this FS was developed for regions with higher altitudes.

Regarding the impact of CLR on coffee yield, this study did not assess such variable, mainly because of the high yield variability between plants, regions and seasons and their influence on the ongoing and subsequent seasons (Kushalappa et al. 1983).

Table 2. Rankings of coffee leaf rust control treatments for the field trials conducted during 2015-16 and 2016-17 seasons in several locations in Minas Gerais and São Paulo states, Brazil. The best control protocol is in the top, based on AUDPC.

2015-16		2016-17				
Varginha	Boa Esp.	Varginha	Boa Esp.	Uberlândia	Buritizal	Campinas
T4 a*	T3 a	T3 a	T6 a	T4 a	T4 a	**T2 a**
T2 a	T4 a	T4 a	T4 a	T3 a	T3 a	T5 b
T5 a	**T2 a**	**T2 a**	**T2 a**	T5 a	T6 b	T6 b
T3 b	T5 a	T5 a	T5 a	T6 a	T5 c	T3 b
T6 b	T6 a	T6 a	T3 a	**T2 a**	**T2 c**	T4 b
T1 c	T1 b	T1 b	T1 b	T1 b	T1 d	T1 c

Boa Esp. = Boa Esperança; *Values followed by the same letter on the column are not significantly different at $\alpha = 0.05$ according to the Scott-Knott cluster analysis procedure.

Disease forecast systems have been used in agriculture since 1962, with the late blight in potato predictor system reported by Wallin (1962). Another example is FAST (Forecast System for *Alternaria solani* on Tomato) system as described by Pitblado (1992). However, all these attempts were not successful in the past because of the difficulties faced by growers to manage the models and to record weather data, mainly leaf wetness duration. In the proposed CLR warning system, both problems were overcome, once the model is very simple and weather variables commonly observed in regular weather stations are necessary, making possible to calculate spray dates with several days in advance.

For running the CLR forecast system appropriately, daily minimum air temperature and average relative humidity are required. Even considering its simplicity, in Brazil, there are large areas without weather stations, which can be a barrier for CR FS use. The growers' first option to cope with this problem is buying a simple weather station, which needs regular maintenance in order to ensure that the data measured correspond to the reality. The second option is to use interpolated data from the INMET network in the region. For air temperature interpolation, it is easier since there is a strong and predictable spatial correlation between latitude, longitude and terrain elevation with air temperature variation (Daly et al. 2008). For relative humidity, the interpolation can be better done using geographical interpolation methods, like kriging or inverse distance square (Xavier et al. 2015).

As stated by McCook and Vandermeer (2015), farmers frequently do the fungicides sprays incorrectly. The FS here proposed resulted on better control, mainly when regionally calibrated. In general, T4 was the protocol with the best disease control, followed by T3. However, T5, with only two sprays, resulted in a performance as good as T4 and T3. As the proposed model is easy to use and performed well in most cases, even without site specific measurements, it can be a useful tool to help coffee growers to control CLR in a more rational way.

3.4. Conclusions

According to the results obtained in this study, the following conclusions were established:

a) All protocols used for the CLR control based on the FS were efficient to recommend fungicide sprays;
b) Protocols used in T4 and T3 were the best ones in terms of CLR AUDPC, however, T5, in average with one spray less, was as efficient as T4 and T3 for CLR controlling;
c) The poorest performance of CLR FS for controlling the disease in Campinas indicates that thresholds of the protocols tested should be regionally adjusted, since the CLR infection rate model used is empirical.

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4. AGRO-CLIMATIC FAVORABILITY INDEX FOR COFFEE LEAF RUST IN BRAZIL

ABSTRACT

Arabica coffee is an important commodity for Brazilian agriculture and covers around 1.5 million hectares in the country, mainly in Minas Gerais, São Paulo, and Espírito Santo states. Coffee leaf rust (CLR) is the major coffee disease and threatens this crop worldwide, with high impact on Brazilian coffee production. Climate conditions for coffee and CLR grown are very similar, which favor disease outbreaks. However, the disease intensity varies among regions and seasons, which shows that interannual and spatial climate variability is a key aspect for epidemics. As coffee crop is perennial, the definition of the cultivar to be planted is determinant for disease occurrence, once CLR epidemics are more intense on susceptible plants. Therefore, is important to assess the CLR risk of occurrence in a given region, based on the source of inoculum and climatic conditions in order to determine the best cultivar to be planted and the strategies of control in an established crop. The present study analyzed 46 sites in the main Brazilian coffee regions to determine their favorability for CLR occurrence. Weather data from 1961 to 2015 were employed to run a coffee rust infection rate estimation model for every available season, considering a season as the period between 1 October and 30 June. The daily estimated infection rates were accumulated along each growing season of the historical series, returning the cumulative infection rate (CIR) for each one. The site-season were classified into five favorability classes (Very Low, Low, Medium, High, and Very High). The integration of the results of all seasons allowed to calculate the agro-climatic favorability for CLR occurrence for each site. The agro-climatic favorability values were spatialized in the whole studied region, comprising the states of Paraná, São Paulo, Rio de Janeiro, Espírito Santo, Bahia, Minas Gerais, and Goiás. The map was classified into four different classes, named as Very Low, Low, Medium, and High CLR risk. The results showed that most of the currently cultivated areas are within Medium to High CLR risk. On the other hand, some regions suitable for coffee production were identified as having Very Low or Low CLR, as observed in northwestern Paraná, western São Paulo, central Bahia, and northern Minas Gerais. The CLR risk map presented in this study is a useful tool for selecting cultivar for new areas or where the plantations are being renewed and for stablishing the strategy of CLR control in the area.

Keywords: *Hemileia vastatrix*; Climatic risk assessment; Disease management planning;

4.1. Introduction

In Brazil, coffee is an important commodity to the economy, mainly for the states of São Paulo (SP) and Minas Gerais (MG) (Souza et al. 2011). *Coffea arabica* (arabica) and *Coffea canephora* (robusta) are the two species grown in 2 million ha in the country and arabica accounts for 75% of all areas planted (Instituto Brasileiro de Geografia e Estatística (IBGE) 2017a), mainly cropped in MG, SP, and Espírito Santo (ES) states, covering highlands of the southeastern region, between latitudes 18 and 23 ºS.

Arabica coffee is originated from tropical highlands in Ethiopia, between 6 and 9º N, with annual average temperatures around 18 to 20 ºC, a Csb subtropical climate due to the high elevations. Minimum temperatures are above 4 ºC and maximum up to 31 ºC. Rainfall in this Ethiopian region ranges from 1500 to 1800 mm, with a dry and cold season from December to February (Camargo and Pereira 1994).

Coffee leaf rust (CLR) threatens coffee plantations worldwide (Camargo 2010). In Brazil, CLR outbreaks are observed every year, reducing yields by around 30% when chemical control is not applied (Kushalappa 1989b; Capucho et al. 2012). Different coffee growing regions around the world have faced or are facing yield reduction due to CLR. This disease was firstly reported in Sri Lanka around 1868, hindering profitable production of arabica coffee in the country (Camargo and Pereira 1994). The first occurrence of CLR in Brazil was in 1970 in the south of Bahia state, and within four months, it spread to most coffee plantations in the country (Chaves et al. 1970). Besides Brazil, the pathogen is currently present in Peru, Ecuador, Colombia, and Central American countries (Avelino et al. 2015).

CLR development requires moderate temperature and high humidity, conditions similar to those found in the arabica coffee producing regions. Favorable temperature required for more than 20% of the *Hemileia vastatrix* Berk. et Br. uredospores infection in laboratories experiments ranged from 18 to 26 ºC, when at least 8 h of free water on the leaves were available (Kushalappa et al. 1983). High levels of sporulation normally occur during the rainy period (Boudrot et al. 2016).

Boudrot et al. (2016) concluded that weather is the main trigger for CLR epidemics. According to Avelino et al. (2015), the main drivers for CLR epidemics in Central America are weather and economic conditions. Weather conditions affect disease infection and intensity increase, while economic aspects are associated to the chemical control, which leads to higher production costs. As in Brazil most growers have easy access to fungicides than those in Central America, the epidemic trigger is assumed to be mainly the weather conditions.

Besides the chemical control, the use of tolerant cultivars can also be considered as a CLR management method (Kushalappa and Eskes 1989). This means that planning activities are very important in regions with high risk of CLR occurrence, where only chemical sprays are not enough for an effective control.

The analysis of where the host is grown is also pivotal for understanding the epidemics distribution (Weltzien 1972), once it can help to delimit the areas with high potential for spores dispersion. Urediniospores of *Hemileia vastatrix* are spread by wind and may have a long-distance propagation, reaching up to 1 km in the atmosphere and about 700 km away from the CLR uredospore source (Martínez et al. 1975). The spore distribution is highly related to CLR epidemics and is linked to the number of disease lesions, which is a rare assessment (Kushalappa and Chaves 1980). According to Weltzien (1972), if spore distribution is not known, studies on disease distribution are uncertain.

Considering that weather conditions together with cultivar susceptibility and spore presence are the main factors for CLR epidemic, the hypothesis of this study is that is possible to identify the zones of risk for CLR occurrence based on these variables. Based on that, this study aimed to define risk zones for CLR occurrence in Brazil, based on an empirical weather-based model for estimating CLR infection rate, in order to recommend cultivars for new coffee areas and to guide disease control strategies to reduce CLR outbreaks.

4.2. Material and Methods

4.2.1. Location and weather data

This study was conducted for the traditional coffee areas of Brazil, as well as those suitable for crop expansion, in the states of Paraná (PR), São Paulo (SP), Rio de Janeiro (RJ), Espírito Santo (ES), Minas Gerais (MG), Goiás (GO), and Bahia (BA), totaling 46 locations (Table 1).

Table 1. Locations and their respective codes, geographical coordinates, altitude, and total number of seasons available for coffee leaf rust cumulative infection rate (CIR) estimation.

Municipalities	Code	Latitude	Longitude	Altitude (m)	Seasons
Ivaí	1	-25.00	-50.85	808	35
Castro	2	-24.78	-50.00	1009	44
Campo Mourão	3	-24.05	-52.36	616	45
Maringá	4	-23.40	-51.91	542	40
Londrina	5	-23.31	-51.13	566	51
Presidente Prudente	6	-22.11	-51.38	435	42
Sorocaba	7	-23.48	-47.43	645	34
São Carlos	8	-21.96	-47.86	856	47
São Simão	9	-21.48	-47.55	617	49
Catanduva	10	-21.11	-48.93	570	44
Franca	11	-20.58	-47.36	1026	48
Uberaba	12	-19.73	-47.95	737	39
Araxá	13	-19.60	-46.93	1023	38
Bambuí	14	-20.03	-46.00	661	40
Machado	15	-21.66	-45.91	873	50
São Lourenço	16	-22.10	-45.01	953	50
Lavras	17	-21.75	-45.00	919	48
Juiz de Fora	18	-21.76	-43.35	940	44
Barbacena	19	-21.25	-43.76	1126	51
Viçosa	20	-20.75	-42.85	690	43
Bom Despacho	21	-19.71	-45.36	695	34
Sete Lagoas	22	-19.46	-44.25	732	49
Conceição do Mato Dentro	23	-19.01	-43.43	652	44
Cordeiro	24	-22.01	-42.35	506	38
Itaperuna	25	-21.20	-41.90	124	43
Caparaó	26	-20.51	-41.90	843	38
Vitória	27	-20.31	-40.31	36	40
Caratinga	28	-19.73	-42.13	609	38
Pirapora	29	-17.35	-44.91	505	35
Diamantina	30	-18.23	-43.64	1296	37
Itamarandiba	31	-17.85	-42.85	1097	45
Araçuaí	32	-16.83	-42.05	289	44
Salinas	33	-16.16	-42.30	471	37
Janaúba	34	-15.78	-43.30	516	33
Pedra Azul	35	-16.00	-41.28	649	40
Vitória da Conquista	36	-14.88	-40.79	874	37
Ituaçu	37	-13.81	-41.30	531	36
Caetité	38	-14.06	-42.48	882	48
Bom Jesus da Lapa	39	-13.26	-43.41	439	41
Lençois	40	-12.56	-41.38	439	45
Catalão	41	-18.18	-47.95	840	52
Pirenópolis	42	-15.85	-48.96	740	35
Formosa	43	-15.53	-47.33	935	39
Formoso	44	-14.93	-46.25	840	34
Arinos	45	-15.90	-46.05	519	34
Taguatinga	46	-12.40	-46.41	604	45

Weather data from these sites in the coffee production regions were used in this study (Figure 1). These data were obtained from National Institute of Meteorology (INMET) database, for the period between July 1961 and August 2015. The daily relative humidity and minimum air temperature were acquired from the historical database. The altitude of the considered region ranged from sea level up to mountains with more than 2600 m. As consequence of the dimension of the region, different climates are found: humid subtropical without (Cf) and with (Cw) dry winter; tropical rainforest climate (Af); tropical monsoon climate (Am); tropical savanna (Aw); and semi-arid (BSh), according to Köppen climate classification (Alvares et al., 2013).

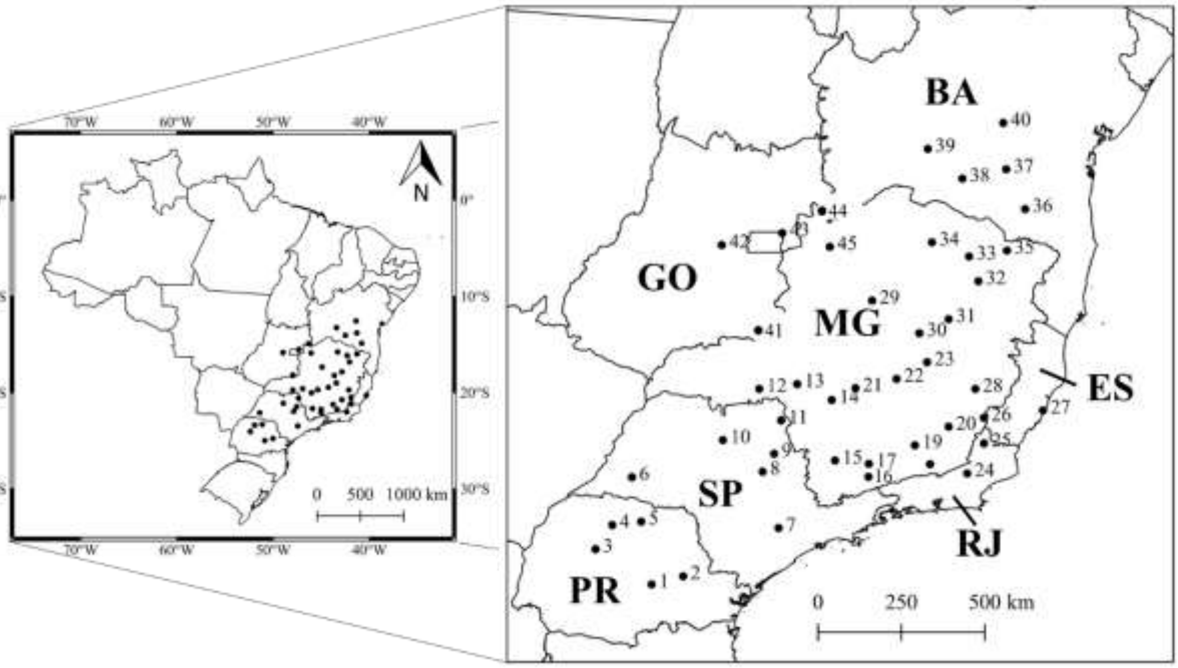

Figure 1. Locations employed for determination of the coffee leaf rust risk zones in Brazil, comprising the states of Paraná (PR), São Paulo (SP), Rio de Janeiro (RJ), Espírito Santo (ES), Goiás (GO), Minas Gerais (MG), and Bahia (BA).

4.2.2. Coffee leaf rust infection estimation

Daily infection rates for CLR were calculated according to the model presented in Chapter 1. The model considers air minimum temperature and average relative humidity to calculate daily infection rate. This model is the result from correlations of 88 CLR assessments in three different sites in Brazil. The CLR epidemic period (hereafter named as season) was defined as ranging from 1 October to 30 June. The sum of the daily infection rates during this period was defined as the cumulative infection rate (CIR). CIR was calculated for every available season for all 46 sites, resulting in a range from 0.58 until 163.16 (Figure 2), totalizing 1923 site-season.

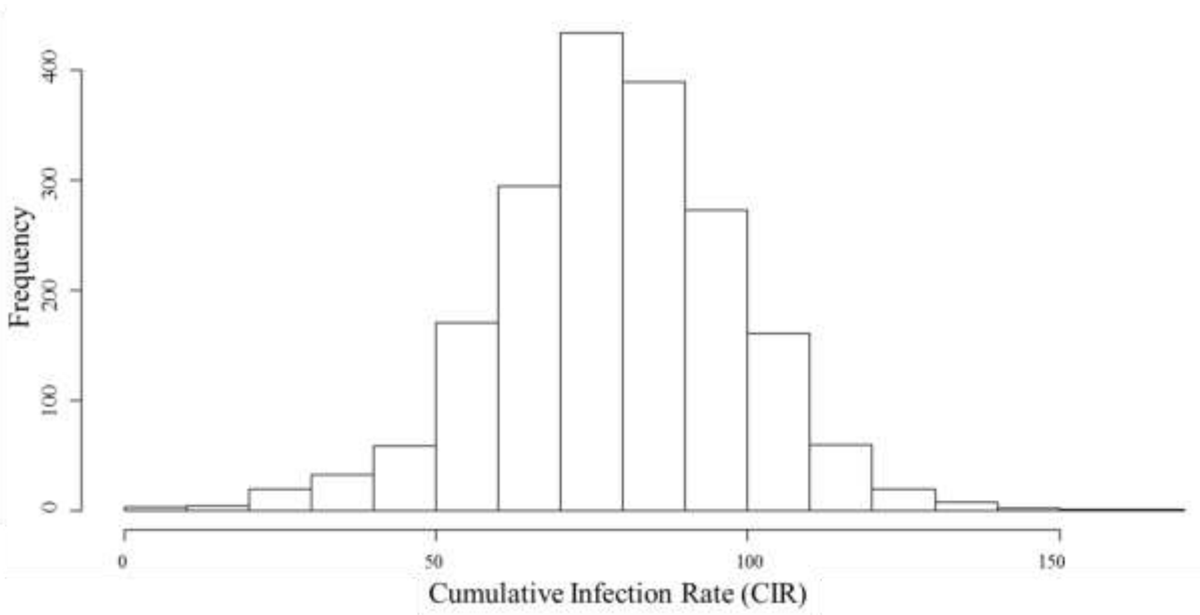

Figure 2. Histogram of cumulative infection rate (CIR) distribution for coffee leaf rust in 46 Brazilian locations, for the period between 1961 and 2015.

A season was considered available when the data required for running the CIR model was complete for at least 265 of the 273 days of the season. A climatic risk for coffee leaf rust (CRCLR), based on Sentelhas et al. (2016), was calculated by considering CIR values of each site and season and the score class of each season. CIR was classified in five classes of intensity (Table 2), considering the CIR distribution (Figure 2). A score of disease intensity was associated with each class, weighting the estimated CIR with the frequency of seasons of its occurrence, during the climatic series above mentioned, and with an empirical factor (Equation 4.1).

$$CRCLR_{calc} = \frac{yVL*0 + yL*1 + yM*2 + yH*3 + yVH*4}{10} \qquad \text{(Equation 4.1)}$$

where: $CRCLR_{calc}$ is the calculated CRCLR; yVL is the frequency of seasons with the Very Low CIR; yVL is the frequency of seasons with Low CIR; yVL is the frequency of seasons with Medium CIR; yH is the frequency of seasons with High CIR; and yVH is the frequency of seasons with Very High CIR. The score values (0 to 4) were chosen in order to give weight of each class for coffee rust favorability in the given region.

Table 2. Coffee leaf rust cumulative infection rate (CIR) range of values per each class and score, to classify each site-season for the period of 1961 to 2015 in Brazilian coffee regions.

Class	Score	CIR Range
Very Low	0	≤ 30
Low	1	30.1 and 60
Medium	2	60.1 and 90
High	3	90.1 and 120
Very High	4	> 120

The risk map was obtained by spatializing CRCLR. For this purpose, a multiple linear regression model was generated, correlating CRCLR of each location with its geographical coordinates (latitude and longitude) and altitude, and their combinations:

$$CRCLR_{est} = a + b*\varphi + c*\lambda + d*h + e*\varphi*\lambda + f*\lambda*h + g*\varphi*h + h*\varphi^2 + i*\lambda^2 + j*h^2,$$

where: CRCLRest is the estimated CRCLR for each location (pixel); φ is the latitude in decimal degrees; λ is the longitude in decimal degrees; h is the altitude in meters; and 'a' to 'j' are the regression coefficients. The selection of the independent variables used in this model was based on the highest final Pearson coefficient of correlation (R).

4.2.1. Coffee leaf rust risk map

The maps were obtained with the software QGIS 2.18. Altitude layers were obtained from digital elevation model (DEM), from 'NASA Shuttle Radar Topographic Mission' (SRTM), in a pixel resolution of 90 x 90 m. The tiles were downloaded from 'http://www.cnpm.embrapa.br/projetos/relevobr/download/ and merged using 'Raster' > 'Miscellaneous' > 'Merge' tools. As the area of coffee cultivation is relatively broad, map processing required a reduction in the resolution to 900 x 900 m, using the 'Raster>Projections>Warp (Reprojection)', function 'Resize'. The geographical coordinates were also obtained from the SRTM layer, separated in latitude and longitude, and processed together with altitude as three different raster layers. Coefficients of the multiple linear regression were then inserted into the 'Raster calculator' function in order to calculate the $CRCLR_{est}$ value of each pixel in the map.

The mean absolute error of the equation was estimated for each site. A map of these errors was also generated by means of 'Raster interpolation', Inverse Distance Weighting. To increase map accuracy, the 'map of errors' was added (using 'Sum' function) to the climatic favorability map.

Minimum air temperature and average relative humidity maps were also generated by multiple linear regression procedure, based on the average of each weather variable in each site during the period of CIR calculation, and subsequently spatialized in the 'Raster calculator' tool. Finally, the map of coffee crops in Brazil was obtained using the areas of each site with coffee plantations from IBGE (2017), associated with the geographical coordinates. The file with this information was processed using the 'Inverse Distance Weighting' Interpolation, with the distance coefficient "P" set to 5.

4.3. Results and Discussion

4.3.1. Coffee productions areas in Brazil

Arabica coffee is produced in seven different regions in Brazil, being three of them large and grouped and four small and dispersed (Figure 3). These areas are hereafter denominated as follows: i) South of MG - the largest area located on the border between northeastern SP and southern MG, with 612,404 ha cropped with coffee, corresponding to 40% of the total Brazilian arabica coffee area; ii) East of MG and ES – which includes the southern part of ES, the easternmost region of MG and a small portion of northern RJ, all in the mountains, with 404,979 ha; iii) West of MG or 'Cerrado Mineiro' – an area with 163,938 ha, in the Patrocínio region, the municipality with the highest coffee area in Brazil (32,882 ha). The small areas are: iv) northern PR state, which also include the border with south of SP, covering 45,065 ha; v) central SP, in Marília region, with 26,694 ha; vi) northeastern of MG, in the municipalities of Capelinha and Itaipé, with 19,690 ha; and vii) in center-southeastern BA, the northernmost region of this study, with four different areas under cultivation, totaling 112,252 ha. The areas in the state of BA indicate a new region to where coffee plantations are expanding in the country, while the other regions are well consolidated. In GO and western BA, there are also coffee areas according to IBGE (2017), but with small cropped areas.

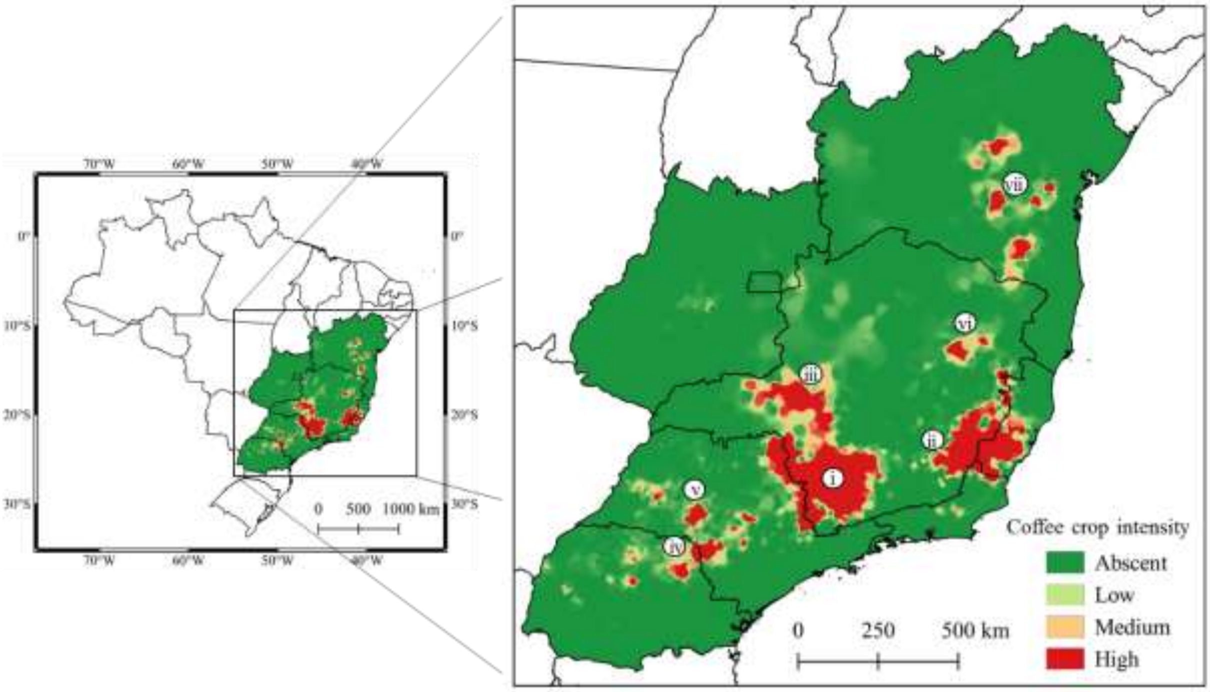

Figure 3. Spatial distribution of arabica coffee crops in Brazil. The numbers show the largest crop concentrations: i) South of MG; ii) East of MG and ES; iii) West of MG; iv) north of PR; v) central of SP; iv) northeast of MG; vii) center-southeastern BA.

The map of Figure 3 depicts a possible host structure as inoculum source for CLR epidemics. *Hemileia vastatrix* is considered a biotrophic fungus, as it requires living coffee leaves to proliferate (Boudrot et al. 2016). Therefore, uredospores that generate new lesions originate from the surrounding areas where CLR is occurring. One lesion can produce between 300 and 400 thousand uredospores during two months, resulting in great inoculum potential (Kushalappa and Eskes 1989).

As CLR occurs anywhere in the Central and South America (Camargo and Pereira 1994), the inoculum potential increase where there are more coffee areas. Arabica coffee areas in Brazil are basically cultivated with genotypes susceptible to CLR infection (Honorato Jr et al. 2015). As the percentage of leaf area with spore is the biological variable most related to CLR development (Kushalappa and Chaves 1980), lower the area with coffee plantations in the region less conducive it is for outbreaks, since percentage of spore production area is lower.

4.3.2. Climatic risk for coffee leaf rust

CRCLR calculated for the 46 locations in Brazil ranged from 11 to 31 (Figure 4), which represents a large range due to variation in CLR favorability in the region. As expected, the disease does not have the same risk of occurrence in different localities in Brazil, since the climatic conditions are different. Even in a same coffee region the risks can be different due to spatial and interannual climate variability. To know how this risks varies according to weather conditions is an important aspect to predict diseases, as mentioned by Yuen and Mila (2015).

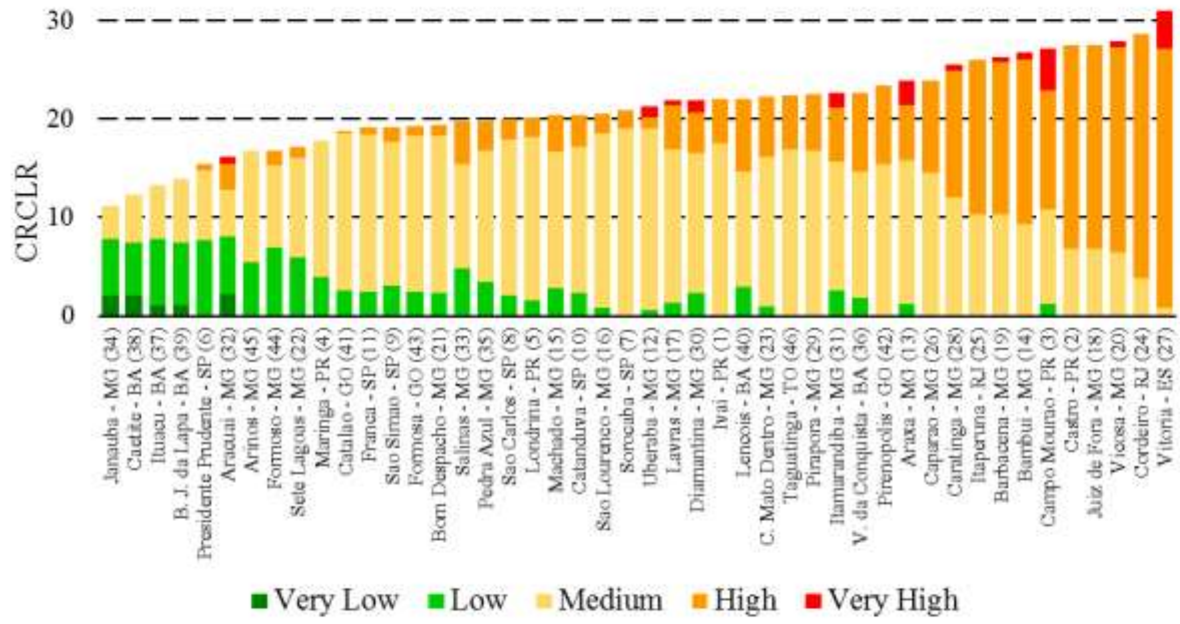

Figure 4. Climatic risk for coffee leaf rust calculated for 46 locations in Brazil. Colors represent the number of coffee growing seasons with each risk class, proportional to the bar size, and number of seasons assessed. Site codes (numbers) are between brackets.

The distribution of risk score classes for each location depended on weather variability between the growing seasons when CLR development occurred. Vitória, the site with the highest CRCLR is a location with low weather interannual variability, with 85% of the seasons with High risk, 12.5% with Very High risk, and only 2.5% with Medium risk. As this location had 40 growing seasons analyzed, 39 out of 40 seasons were with High or Very High risk.

Conversely, Janaúba presented mainly Very Low and Low risk, representing 6 and 17, respectively, of 33 seasons analyzed, while the other 10 seasons were with Medium risk. Araçuaí was the location with the highest risk variability, being the only site which presented all five risk classes in 44 seasons. The most frequent risk classes for this location were

Medium and Low (Figure 4). Both Janaúba and Araçuaí have As Köppen´s climate (Alvares et al. 2013), in northern Minas Gerais, with low rainfall, low RH and high minimum temperatures (Figure 5). Although the low rainfall, this region is characterized by high rainfall variability (up to 300%) between seasons, which directly influences RH and temperatures (Kousky and Chu 1978).

The regression coefficients for minimum air temperature and average relative humidity, are shown in Table 3. For the analysis of relative humidity, R and MAE of the multiple linear regression are 0.809 and 2.1, very similar to 0.851 and 5.528 obtained by Xavier, King, and Scanlon (2015). Although R is straightly smaller, MAE is also smaller, resulting in smaller estimation errors. Xavier, King, and Scanlon (2015) obtained their best RH map using the angular distance weighting interpolation method, different than the inverse distance weighting applied for either variables present in Figure 5. In Xavier, King, and Scanlon (2015) study, the minimum temperature presented R of 0.906 and MAE of 1.3. Comparing these results with the presented here, both RH and minimum temperature maps are similar.

Table 3. Multiple linear regression coefficients and statistical errors for spatialization of minimum air temperature and average relative humidity.

Coefficient	Minimum Temperature		Relative Humidity	
a	7.509		66.37	
b (lat)	-0.51	R = 0.954	-0.428	R = 0.809
c (long)	-0.392	d = 0.976	-0.246	d = 0.886
d (alt)	-0.00519	c = 0.931	-0.00685	c = 0.717
e (lat*long)	-0.0111	MAE = 0.41ºC	-0.0654	MAE = 2.1%
f (lat*alt)	0.000117		0.000596	
g (long*alt)	0.0000567		-0.000571	
h (lat^2)	-0.00711		0.109	
i (alt^2)	0.00000365		-0.0000000699	

R = Pearson's coefficient of correlation; d = Wilmott's Agreement index; c = Confidence index; MAE = mean absolute error (ºC and %). Letters a to i are the coefficients of the multiple regression.

Uberaba, Cordeiro, São Lourenço, Sorocaba and Vitória had more than 85% of the growing seasons within the same risk class, showing more stable weather conditions among the years. Of 46 sites studied, 19 did not show large variability between seasons, with more than 70% of the seasons in a same class. The areas with the highest risk are defined as where CLR epidemics occur regularly, mainly in the cultivars with low level of tolerance to CLR. In these regions, coffee yield and/or quality reductions are inevitable, resulting in regular economic losses (Weltzien 1972). These regions are those where most seasons were classified as Very High and/or High classes (Figure 4), mainly in RJ and ES, southern MG, PR state, and southwestern GO.

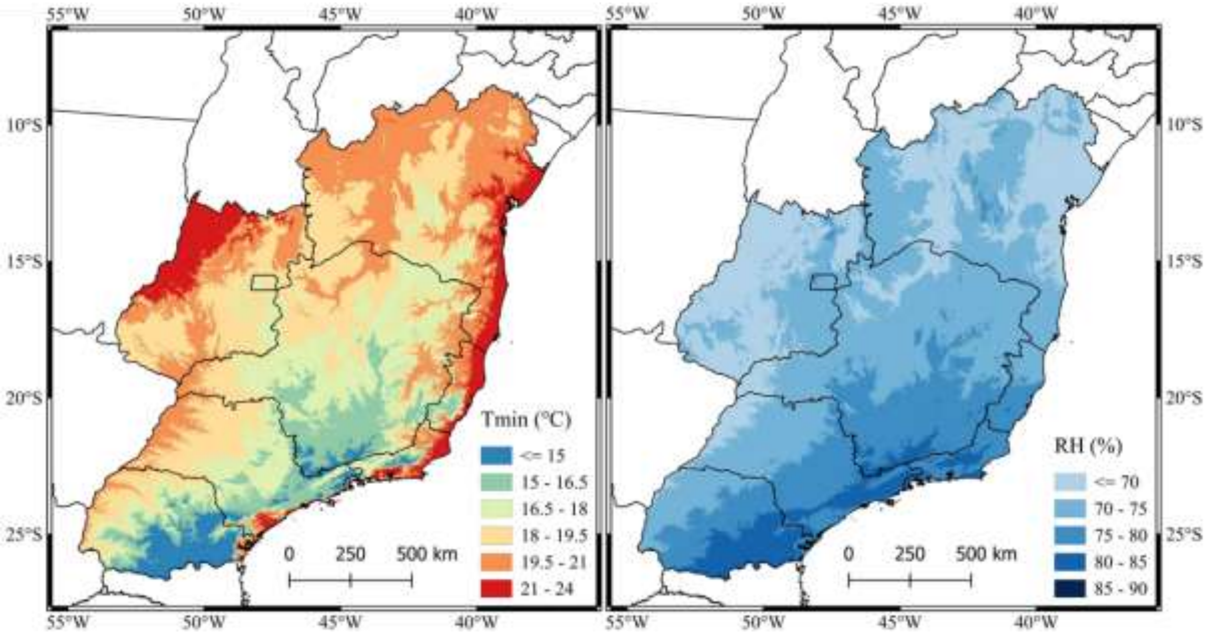

Figure 5. Minimum air temperature and average relative humidity, during the favorable period for coffee leaf rust, from 1 October to 30 June, in the states where coffee is produced in Brazil.

4.3.3. Estimated climatic risk for coffee leaf rust

The multiple linear regression, based on latitude, longitude, altitude, and their combinations were used to generate a model for estimating CRCLR ($CRCLR_{est}$) for each pixel of 900 by 900 m, and the coefficients are presented below. The Pearson coefficient of correlation 'R' of this linear model was equal 0.76 ($p \leq 0.01$).

$$CRCLR_{est} = 401.752 - 10.533*\varphi + 20.284*\lambda - 0.055*h - 0.270*\varphi*\lambda - 0.001*\varphi*h - 0.001*\lambda*h + 0.058\varphi^2 + 0.264*\lambda^2 + 0.001*h^2.$$

where: φ is the latitude in decimal degrees; λ is the longitude in decimal degrees; h is the altitude in meters.

CRCLR$_{est}$ in Brazil has different levels according to weather characteristics (Figure 6). Weltzien (1972) proposed three zones for differentiation between disease risk areas: area of main damage, marginal damage, and sporadic attack. In the present study, four zones were considered for giving more details in terms of disease risk. Most of SP state has Low or Medium risks for CLR. This state has a large potential for expansion on coffee plantations, according to the agro-climatic zoning presented by Assad et al. (2004). CRCLR$_{est}$ is Low in the entire western and central regions, while the eastern region has Medium risk. Few areas of Very Low risk are observed in southern coastal area and in the western part of the state, known as Presidente Prudente region, also presented in Table 2. High risk is evidenced in the eastern region, represented by the Vale do Paraiba, North coast, and Serra da Mantiqueira. It also happens in the south border of SP with PR. Similar disease patterns were also observed by Sentelhas et al. (2016) when mapping sugarcane orange rust risk for São Paulo state and by Soares-Colletti, Alvares, and Sentelhas (2016) when mapping the risks for citrus post-bloom fruit drop.

ES, center-northern RJ, eastern MG, part of PR and southwestern GO are also considered as regions of High risk for CLR. Northwestern GO is considered a region of Medium risk due to high minimum temperatures, even presenting low RH during CLR favorable period (Figure 6). In this region, low RH is the limiting factor for CLR outbreaks which makes conditions favorable for epidemics only during the rainy seasons when RH increases. GO has few coffee plantations and this map shows one of the reasons for that, the Medium to High CRCLR in the highland where coffee could be suitable. However, such limitation could be solved by using CLR-tolerant cultivars and/or a rational chemical control.

Temperatures as high as those observed in northwestern GO also happen in central BA, mainly in the São Francisco River valley, where RH is low, both resulting in a Very Low CRCLR (Figure 6). The surrounding areas to the west and east are of higher altitudes, leading to lower temperatures and higher RH, which increase the CLR risk, being Low.

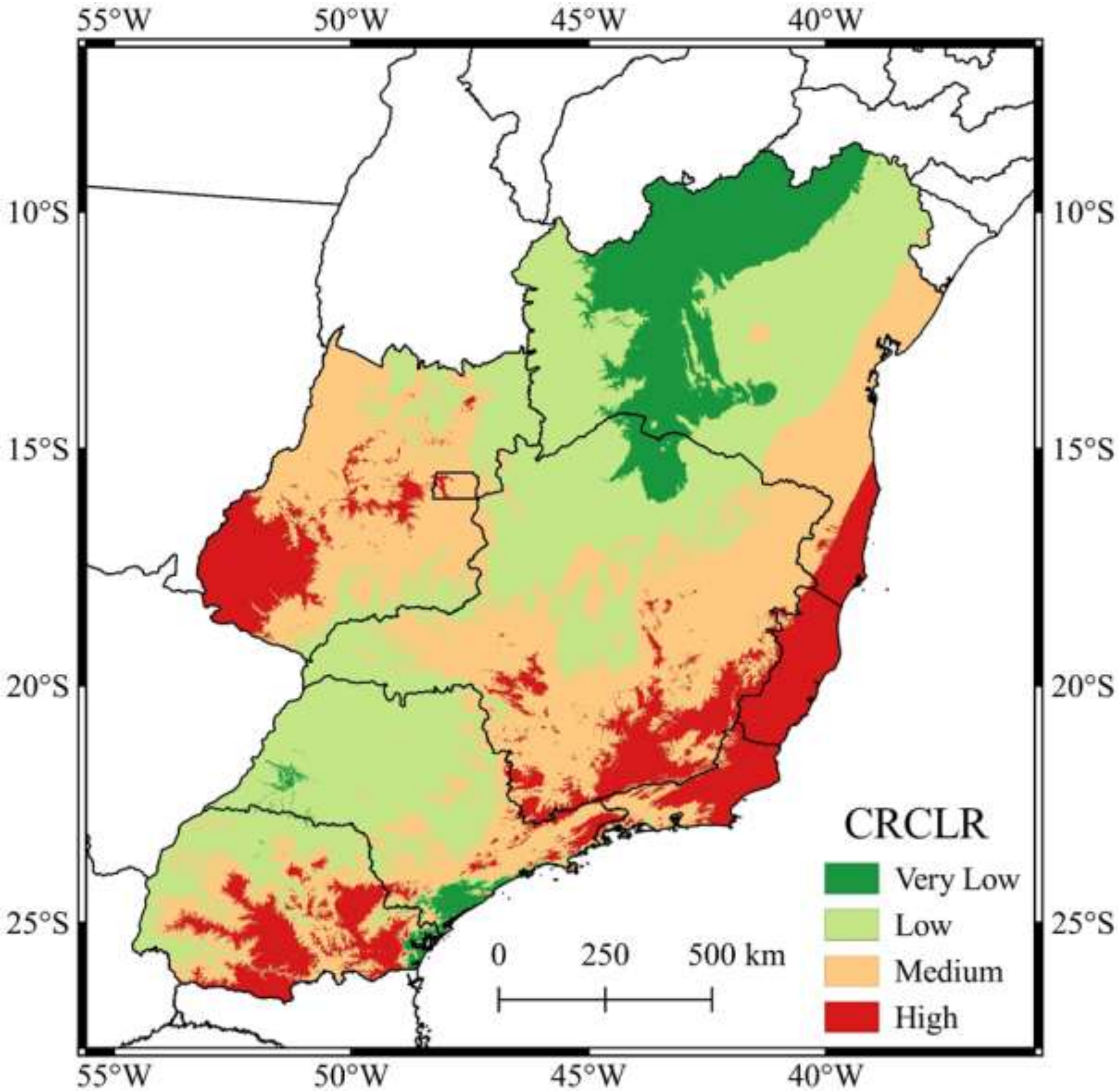

Figure 6. Climatic risk for coffee leaf rust (CRCLR) estimated for the Brazilian states where coffee is produced.

The coastal areas in the southeastern BA, all ES state and great part of RJ is of high risk for CLR outbreaks (Figure 6) and, therefore, they are not recommended for arabica coffee plantations (Assad et al. 2004). Despite High risk for CLR, in these regions there is a predominance of warm and wet weather, with temperatures above 34 °C, which promote conditions for flower abortion, decreasing coffee yields drastically (Sediyama et al. 2001). Exception is the highland in the border between ES and MG, where the weather conditions are more suitable for the coffee plants and less favorable for CLR.

The most areas with High risk for CLR are not cultivated with arabica coffee, as can be seen in southern PR and the entire GO state (Figure 6). The exceptions are in southern and southeastern MG and western ES, which are traditional coffee regions. The High risk for CLR occurrence in these areas results in severe outbreaks due to the combination of two main factors: high inoculum source (Kushalappa and Chaves 1980) and favorable weather conditions (Zambolim 2016).

In PR state, the southern area is predominantly Medium to High risk to CLR. Moreover, this area also has high risks to frosts (Assad et al. 2004), therefore unsuitable for coffee plantation. However, at the north of the state, around 24 ºS, frost risk is lower (Assad et al. 2004) and CRCLR varies from Low to Medium (Figure 6), which justify the currently presence of coffee plantations there (Figure 3). Suitable areas for coffee, with Low to Medium CLR risk, are also observed to the west of the present coffee areas (Figure 6), where frosts risks are also low (Assad et al. 2004).

As the main Brazilian coffee regions are presently in zones of Medium to High CLR risk, outbreaks normally occur every season, requiring constant chemical control, which varies in intensity depending on the weather conditions. Therefore, the map presented in Figure 6 is a useful tool, which combines GIS and weather-based disease model, in order to recommend cultivars for new coffee areas and to guide disease control strategies to reduce CLR outbreaks.

4.4. Conclusions

The use of a GIS coupled with a weather-based CLR infection rate model was able to define the risk zones for CLR outbreaks in Brazil. Based on that, cultivars can be chosen for new plantations and a more reliable CLR control strategy can be planned. Mostly of the currently cultivated areas present Medium to High risk, while other suitable areas present Very Low and Low risk. It characterizes the expansion potential with CLR reduced risk.

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5. ASSESSING BIOGEOGRAPHY OF COFFEE RUST RISK IN BRAZIL AS AFFECTED BY EL NIÑO SOUTHERN OSCILATTION

ABSTRACT

El Niño Southern Oscillation (ENSO) is an oceanic-atmospheric phenomenon influencing worldwide weather and climate. Its occurrence is determined by the sea surface temperature (SST) anomaly of the 3.4 Niño region in Pacific Ocean (5°N-5°S, 120°-170°W). El Niño (EN), Neutral (NT), and La Niña (LN) are the three possible phases of ENSO, respectively for warm, normal and cold SST anomaly. Such as in other regions around the world, Brazilian weather is also influenced by ENSO phases. The country is the major coffee producer in the world, and production is totally associated to weather conditions, which affect both plants growth and their interactions with microorganisms. Coffee leaf rust (CLR) is a coffee disease caused by the fungus *Hemileia vastatrix*, which is responsible by coffee yield losses. To keep this disease in a minimum intensity chemical control is required every season. As CLR is highly influenced by weather conditions, it is possible to use weather variables to simulate its progress along the crop cycle to make control more rational. Based on that, the aim of this study was to estimate CLR infection rate, based on minimum temperature and relative humidity, to assess the possible ENSO influence on the patterns of this disease in 45 Brazilian sites. Cumulative CLR infection rates (CIR) were daily estimated from October to June of each growing season and location, considering its ENSO phase. The differences between the extremes phases, warm and cold (EN-LN), were assessed. Eight sites, mainly located in Paraná state, have shown evidence of CLR infection rate differences between EN and LN phases (G1). Evidence of no difference of CLR infection rate between EN and LN was found in 18 sites (G2), while 19 sites showed no evidence of differences (G3), due to the large variation of CIR in the same ENSO phase. The G1 sites are mostly located in the Southern Brazil, where ENSO have a well-defined influence on rainfall regime. The G2 sites are mainly located in Minas Gerais state, which characterize as a transition region for ENSO influence on rainfall. The G3 sites are located between the north of Minas Gerais and south of Bahia states, characterized by a sub-humid climate, very dry during the winter, where rainfall can vary up to 300% from one year to another, influencing relative humidity and resulting in a lack of evidence. Therefore, only in Paraná state ENSO has well defined influence on CLR infection rate and, consequently, disease intensity.

Keywords: *Hemileia vastatrix*; Infection rate; El Niño; La Niña

5.1. Introduction

El Niño Southern Oscillation (ENSO) is a large-scale oceanic-atmospheric phenomenon which modifies regional and global air circulation, impacting rainfall and air temperatures regimes around the world (Fraisse et al. 2008; Nam and Baigorria 2015). The phenomenon is characterized by warming or cooling of the Pacific Ocean surface beyond normal, affecting air pressure in the equatorial portion of the Pacific, called the atmospheric effect. This atmospheric effect promotes weakening of trade winds in the warm phase and their intensification in the cold phase, with modifications in global circulation patterns (McPhaden et al. 2006). It is the largest oceanic-atmospheric phenomenon, impacting weather seasonal and interannual variability in several regions around the world, and, consequently, having effects on agriculture and the relationship of the plants with pests and diseases (Ropelewski and Halpert 1987; Berlato and Fontana 2003; McPhaden et al. 2006; Fraisse et al. 2008; Gergis and Fowler 2009).

Three possible ENSO phases are classified as a function of the Pacific Ocean sea surface temperature (SST) anomaly (NOAA 2017): El Niño (SST anomaly ≥ 0.5 ºC); La Niña (SST anomaly ≤ -0.5 ºC); and Neutral (SST between -0.5 and +0.5ºC). In Brazil, the main effects of ENSO are:

a) El Niño (EN) normally causes an above-average rainfall in Rio Grande do Sul, Santa Catarina and Paraná states, which impacts agriculture, occasioning maximum grain yields (Berlato et al. 2005; Alberto et al. 2006) and higher risk for diseases occurrence (Del Ponte et al. 2011). In Northeast Brazil, EN causes below-average rainfall, resulting in agricultural droughts, followed by social problems (Costa et al. 2015). In the Southeast region, where most of the coffee is grown, there is no defined pattern for rainfall, but there is a trend of higher temperatures, mainly at night (Marengo and Camargo 2008; INPE 2016);

b) La Niña (LN) also affects parts of Brazil normally in the opposite way in relation to those created by EN. Therefore, in Southern Brazil rainfall is reduced as well as temperatures, since cold masses can reach the region more frequently. On the other hand, in North and Northeast Brazil, rainfall is better distributed, resulting in favorable conditions for agriculture. In the Southeast region of the country, again a transitional condition is observed, with no defined pattern on weather.

c) Neutral phase (NT), weather conditions tend to be within the normal variability observed in the different regions of Brazil. ENSO warm or cold phases tend to occur every 2 to 7 years and can persist for two or more consecutive years, and rarely fail to re-occur within 10 years (McPhaden et al. 2006).

Considering the importance of ENSO as the largest weather phenomenon worldwide, with different episodes every season and strong impacts on crop yields and disease risk, it is of high relevance to understand how its different phases impact crop yields. In this context, the impacts on plant diseases is also important, since it will define which are the control strategies that need to be adopted (Del Ponte et al. 2011; Kriss et al. 2012; Nam and Baigorria 2015).

Coffee plantation ranks as the fourth most valuable crop in Brazil, with a gross product around US$ 6.57 billion and a planted area around 2 million hectares (Instituto Brasileiro de Geografia e Estatística (IBGE) 2017a). Brazil produced around 55 million 60-kg bags in 2016 (ICO 2017), more than twice the output of the second largest producer, Vietnam. Coffee leaf rust (CLR) is the most economically damaging coffee disease worldwide (McCook 2006). This disease, caused by the fungus *Hemileia vastatrix*, is responsible for up to 35% of disease-related losses where the weather conditions are favorable to the pathogen (Zambolim et al. 1997), mainly for arabica coffee (*Coffea arabica*), which presents more susceptibility for this fungus than robusta coffee (*C. robusta*).

In Brazil the first symptoms of CLR usually appears in December (Meira et al. 2008) and epidemic severity varies according to fruit load, weather and crop management (Avelino et al. 2006). The incubation period ranges from 31 to 65 days in Brazil, which is a bit longer than the 27 to 47 days in Kenya (de Moraes et al. 1976). Although the first symptoms appear in December, the beginning of the infection-favorable period starts in October.

Considering that plant diseases are highly influenced by weather conditions, the disease management decision tools can help to rationalize and optimize disease control as well as to increase spray efficiency (Avelino et al. 2006). The assessment of pathosystems throughout seasons, as output of disease development models, is a reality for climate change purpose (Salinari et al. 2006; Ghini et al. 2011), while studies focused on the interannual climate variability is another possible approach. For CLR, several models have been published (Kushalappa et al. 1983; Meira et al. 2008), but generation of decision support systems for disease risk forecasts is still limited since they require laborious field tests under a large variety of conditions.

CLR epidemics happen frequently in Brazil, considering that the coffee varieties are susceptible, the weather is normally favorable and the pathogen is abundantly present in the producing regions (Zambolim et al. 1997; Meira et al. 2008; Ghini et al. 2011). A better understanding of ENSO phases impact on CLR risk is of great importance for achieving a more effective disease control.

Since the weather conditions affect the major diseases that threaten coffee fields, the hypothesis of this study is that there are differences of CLR epidemics among EN, LN and NT events. Therefore, the objective of this study was to estimate CLR incidence for different locations in the coffee growing region of Brazil (45) and growing seasons (54) and to identify whether the CLR epidemics are ENSO-related, based on Two-One-Sided-Tests (TOST) method (Schuirmann 1987).

5.2. Material and Methods

5.2.1. Weather Data

Weather data from 45 coffee producing regions in Brazil were used in this study. These data were obtained from conventional weather stations from the National Institute of Meteorology (INMET) for the period between 1 July 1961 and 31 August 2015. The weather data used comprised daily relative humidity and minimum air temperature. Figure 1 presents the *C. arabica* producing regions in Brazil from where the weather data were obtained.

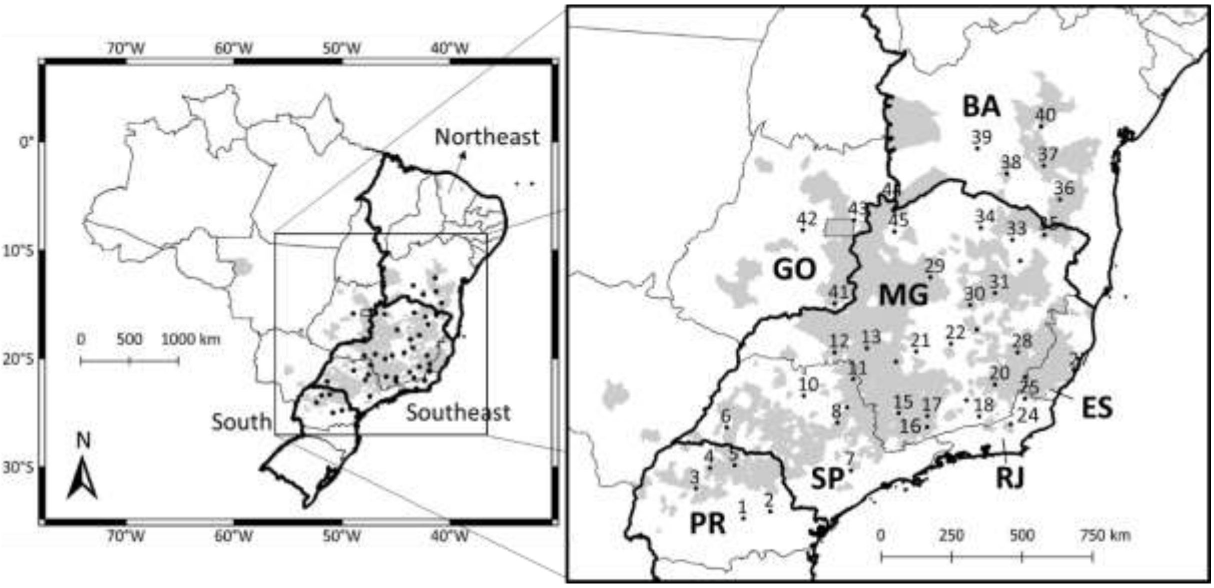

Figure 1. Arabica coffee producing municipalities in Brazil (shaded) with the sites (dots) used for coffee leaf rust infection rate estimation. The states abbreviations are: PR (Paraná), SP (São Paulo), RJ (Rio de Janeiro), ES (Espírito Santo), MG (Minas Gerais), GO (Goiás), and BA (Bahia).

In order to keep the weather data series as complete as possible, missing data were filled up with gridded weather data from Xavier, King, and Scanlon (2015).

5.2.2. Disease estimation model

A model for CLR infection rate estimation, developed with CLR progress curves from a total of 88 site-seasons in the main Brazilian coffee production region, was used to estimate daily CLR infection rate (r_{HN}) (equation 5.1):

$$r_{HN} = -1.293 + 0.019\ Tmin_{(30\text{-}60d)} + 0.017\ RH_{(30\text{-}60d)} \qquad \text{(Equation 5.1)}$$

where: Tmin is daily minimum air temperature and RH is daily average relative humidity. The CLR infection rate (y) was estimated every season from 1 October of year 1, considered as the beginning of the favorable period, till 30 June of year 2, period long enough to cover the entire coffee production season, till mid-July, once CLR latency period in Brazil ranges from 31 to 65 days (Moraes et al. 1976; Kushalappa et al. 1983).

The estimated daily infection rates were summed along each season, which was refered as coffee leaf rust cumulative infection rate (CIR). CIR was used to identify the intensity of CLR risk of each growing season.

5.2.3. El Niño Southern Oscillation

For defining ENSO phases, the U.S. National Oceanic and Atmospheric Association (NOAA) thresholds were used. When Pacific Ocean sea surface temperature in the Niño 3.4 region was equal or above +0.5 °C or equal and below -0.5 °C for 5 consecutive 3-month running averages, EN or LN were established, respectively (NOAA 2017). The Niño 3.4 region (5°N-5°S, 120°-170°W) is the most related portion of Pacific Ocean for monitoring changes associated with ENSO (Lyon and Barnston 2005; McPhaden et al. 2006). When the 5 consecutive 3-month running average was between +0.5 °C and -0.5 °C, the NT condition was established.

As ENSO conditions start at the beginning of the second semester of year 1 and finish at the middle of year 2 (Berlato and Fontana 2003), the weather consequences of ENSO conditions normally affect coffee yield of year 2. The classification of the years from 1962 to 2015 in relation to ENSO phases are presented in Table 1.

Table 1. Classification of ENSO phases for the period between 1962 and 2015, according U.S. National Oceanic and Atmospheric Association (NOAA) method.

ENSO phases		
El Niño	Neutral	La Niña
1964	1962	1965
1966	1963	1968
1969	1967	1971
1970	1979	1972
1973	1981	1974
1977	1982	1975
1978	1984	1976
1980	1986	1985
1983	1990	1989
1987	1991	1996
1988	1993	1999
1992	1994	2000
1995	1997	2001
1998	2002	2008
2003	2004	2011
2005	2006	2012
2007	2009	
2010	2013	
2015	2014	
2016		
20	19	16

* Source: NOAA – http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ ONI_v5.php.

5.2.4. Data Analysis

The difference between CIR of each season available for the study, within each site, during EN and LN conditions was evaluated by the Two-One-Sided-Tests (TOST) method (Schuirmann 1987), which was used to test the null hypothesis of non-equivalence. An equivalence test requires a priori specification of equivalence bounds that separate differences that are considered negligible from those that are considered large. For example, if differences in mean CIR between -10 and 10 were considered small but differences > 10 or < -10 were considered large, the equivalence bounds could be set as -10 and 10. The TOST method is equivalent to constructing a (100-2α)% confidence interval for the mean difference and rejecting the null hypothesis at level α when that confidence interval falls completely inside the equivalence bounds. For example, a 90% interval of (-1, 8) is completely inside equivalence bounds of (-10, 10), so its p-value is < 0.05. However, a 90% interval of (-5, 11) is not completely inside (-10, 10), so the p-value is > 0.05.

It was proposed a novel statistical approach to the usual statistical test. This test, with the null hypothesis that two means are equal, is not appropriate (Dixon and Pechmann 2005;

Ranganathan et al. 2015). A large p-value, e.g. 0.4, could be from a small difference that is precisely known or a very large difference that is poorly known. The first supports the conclusion of a negligible effect whereas the second does not. Equivalence tests – the method we used - reverse the usual null and alternative hypotheses (McBride 2005; Wellek 2010). The equivalence null hypothesis is that two groups are not equivalent, i.e. that the difference between two groups is large. This is rejected, i.e. the associate p-value is sufficiently small, when the estimated difference is sufficiently precise and close to 0. When the equivalence null hypothesis is rejected, the data provide evidence of a negligible effect. Due to using equivalence bounds based on a confidence interval for the mean difference between EN-LN we designated this method as confidence intervals method.

Mean CIR for each ENSO phase (EN, NT, or LN) in each site was estimated by fitting a mean model with a first-order autoregressive temporal correlation to all site-season with valid data. Each site was fit separately. Inspection of the autocorrelation function of the residuals indicated that a first-order autoregressive pattern was appropriate at most sites. After that, 90% confidence intervals for the mean difference between EN and LN seasons at each site were calculated. A model with season as a linear trend in addition to the three categories of means was also considered. At most sites, the coefficient for the season trend was not significantly different from 0. At all sites, adding a season trend had minimal effect on the confidence interval for the EN-LN difference. All computations were done in the SAS® software, using PROC MIXED procedure. Once values for some seasons were not available, a spatial exponential correlation structure was used for accounting for potentially irregularly-spaced observations. This structure is a reparameterization of a first-order autoregressive correlation structure. Table 2 presents the sites used for analysis with their respective number of seasons with EN, LN an NT.

Table 2. Sites, their codes, and number of ENSO phases analyzed for coffee leaf rust cumulative infection rates calculation.

			Number of seasons / ENSO phase			
Site	Code	State*	El Niño	Neutral	La Niña	Total
Ivaí	1	PR	11	15	9	35
Castro	2	PR	14	16	14	44
Campo Mourão	3	PR	15	15	15	45
Maringá	4	PR	13	16	11	40
Londrina	5	PR	17	18	16	51
Presidente Prudente	6	SP	15	14	13	42
Sorocaba	7	SP	10	15	9	34
São Carlos	8	SP	15	18	14	47
São Simão	9	SP	18	17	14	49
Catanduva	10	SP	15	15	14	44
Franca	11	SP	17	18	13	48
Uberaba	12	MG	13	15	11	39
Araxá	13	MG	11	15	12	38
Bambuí	14	MG	13	15	12	40
Machado	15	MG	16	18	16	50
São Lourenço	16	MG	17	18	15	50
Lavras	17	MG	16	16	16	48
Juiz de Fora	18	MG	15	16	13	44
Barbacena	19	MG	17	18	16	51
Viçosa	20	MG	14	15	14	43
Bom Despacho	21	MG	10	15	9	34
Sete Lagoas	22	MG	17	17	15	49
Conceição do Mato Dentro	23	MG	13	17	14	44
Cordeiro	24	RJ	11	14	13	38
Itaperuna	25	RJ	14	15	14	43
Caparaó	26	MG	12	15	11	38
Vitória	27	ES	12	14	14	40
Caratinga	28	MG	12	16	10	38
Pirapora	29	MG	12	14	9	35
Diamantina	30	MG	11	16	10	37
Itamarandiba	31	MG	15	17	13	45
Araçuaí	32	MG	15	16	13	44
Salinas	33	MG	12	15	10	37
Janaúba	34	MG	9	15	9	33
Pedra Azul	35	MG	13	15	12	40
Vitória da Conquista	36	BA	12	16	9	37
Ituaçu	37	BA	12	15	9	36
Caetité	38	BA	17	18	13	48
Bom Jesus da Lapa	39	BA	14	15	12	41
Lençois	40	BA	15	17	13	45
Catalão	41	GO	18	18	16	52
Pirenópolis	42	GO	11	15	9	35
Formosa	43	GO	13	16	10	39
Formoso	44	MG	10	15	9	34
Arinos	45	MG	10	15	9	34
Total	45	7	612	714	552	1878

* MG: Minas Gerais; SP: São Paulo; BA: Bahia; RJ: Rio de Janeiro; GO: Goiás; PR: Paraná; and ES: Espírito Santo.

5.3. Results

The EN-LN analysis, representing the extreme phases of ENSO phenomenon, showed no overall impact for CIR in the Brazilian coffee-producing region (Figure 2). For eight sites (hereafter named as Group 1), however, the ENSO phenomenon significantly impacted the risk of CIR, showing evidence of difference. The remaining 37 sites showed no ENSO-related difference in CLR risk, which included 18 sites that showed evidence of no differences (hereafter named as Group 2), and 19 sites that showed no evidence of differences (hereafter named as Group 3).

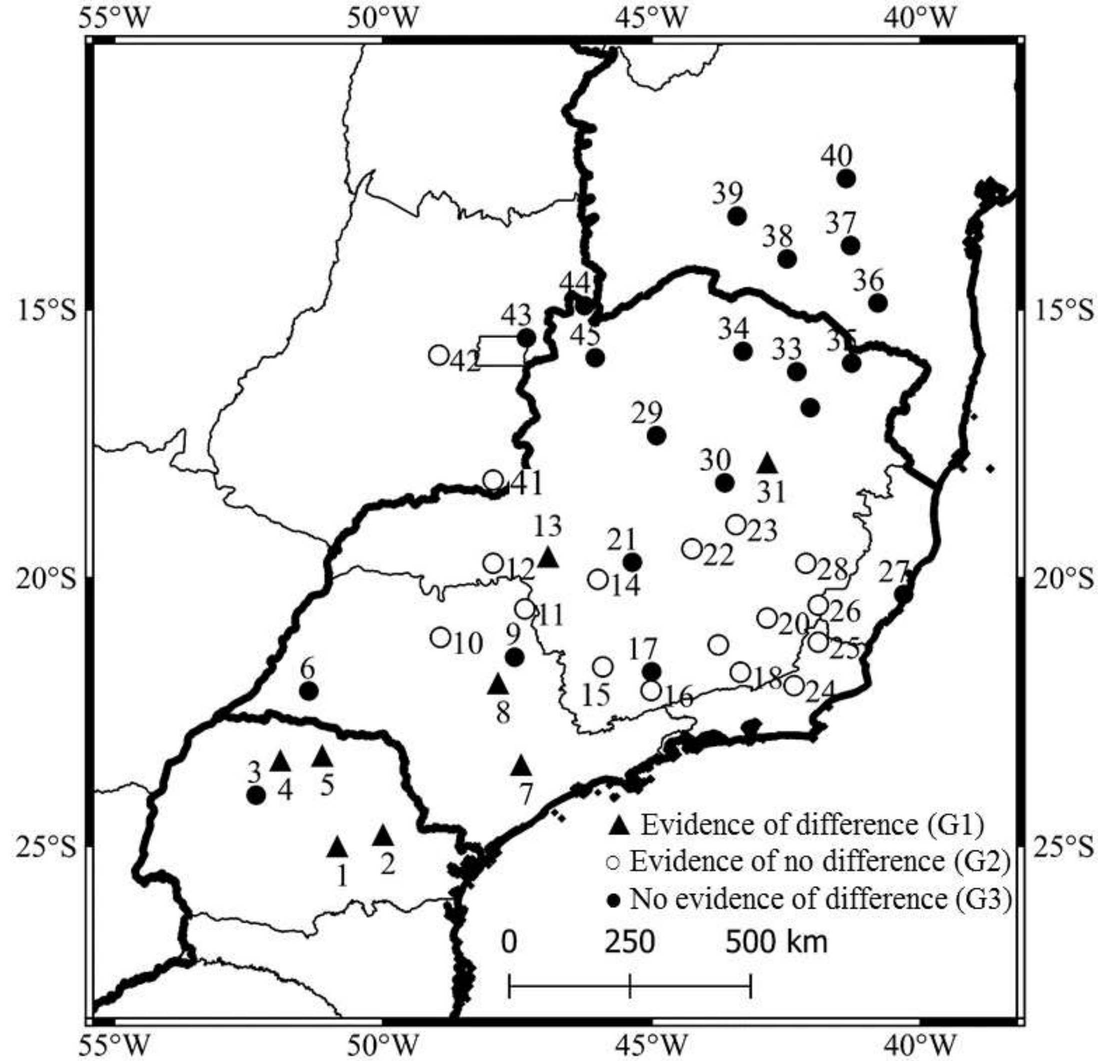

Figure 2. Spatial distribution of El Niño Southern Oscillation effects on coffee leaf rust cumulative infection rate in the Brazilian coffee production regions. Sites with evidence of difference (Group 1 ▲); sites with evidence of no difference (Group 2, ○); and sites with no evidence of difference (Group 3 ●).

The eight sites in Group 1 represented 17.7% of the total (Figure 2). From the five sites located in Paraná state, four presented evidence of difference between EN and LN years (sites 1, 2, 4 and 5). Others are in the state of São Paulo (sites 7 and 8) and Minas Gerais (sites 13 and 31). At all eight sites, EN seasons showed more favorability for CIR than LN (Figure 3).

The sites of Group 2, which showed statistical evidence of no difference in CLR risk between EN and LN (Figures 2 and 3), are mainly located between 17ºS and 23ºS. Only Pirenópolis (code 42) is located in lower latitude than that. The sites of this group are mainly located in Minas Gerais, Rio de Janeiro, São Paulo and Goiás states. The majority of the sites of Group 3, with no evidence of difference (Figures 2 and 3), are in latitudes lower than 17 ºS. The exceptions of are Campo Mourão, PR (3), Presidente Prudente, SP (6), São Simão, SP (9), Lavras, MG (17), Bom Despacho, MG (21), and Vitória, ES (code 27).

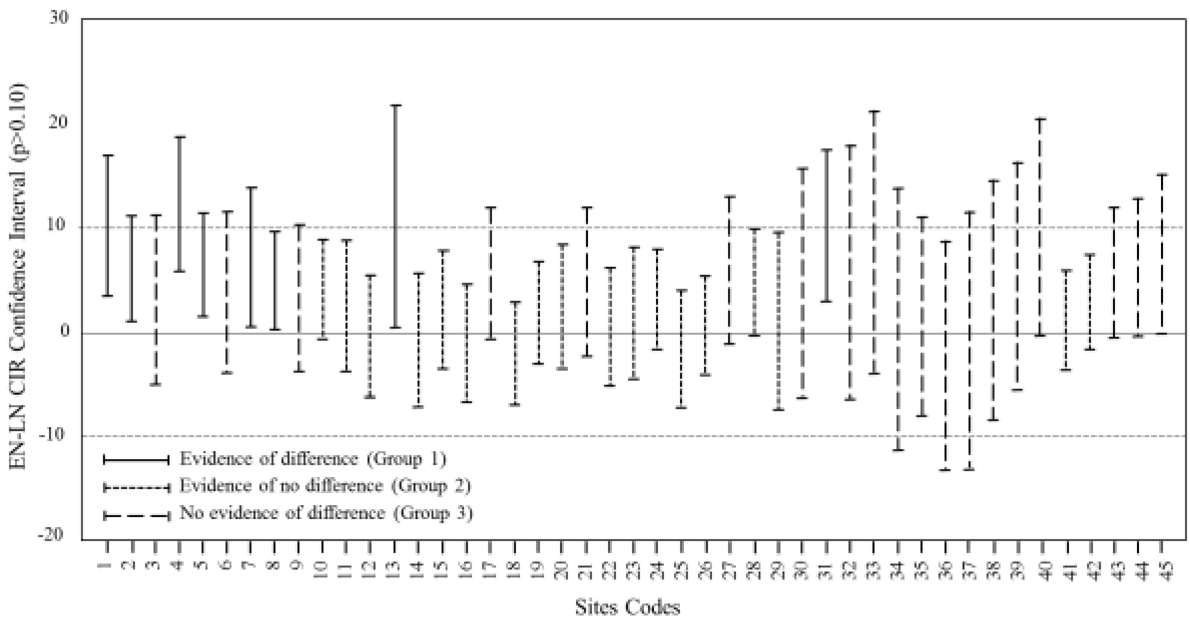

Figure 3. Confidence interval bars of El Niño - La Niña impact on coffee leaf rust cumulative infection rates at 45 sites in the Brazilian coffee producing regions. Bars completely above the 0 line represent evidence of difference between EN and LN for the site (solid lines); Bars completely inside the -10 and 10 bounds represent evidence of no difference between EN-LN seasons for the site (dots); Bars crossing the -10 or 10 bounds indicate no evidence of difference for EN-LN for the site (dashes).

When the extremes of the confidence interval bars occurred between the -10 and 10 bounds, the site shows evidence of no difference of CIR between EN and LN episodes (Group 2). In these situations, the null hypothesis of non-equivalence between the two groups was accepted, due to the precisely known difference between the groups. The 18 sites of Group 2 are located in a geographical transition region for the ENSO phenomenon, mostly between 17° S and 23° S and. Above this line only Pirenópolis (42), in Goiás state shows the same behavior.

Group 3 sites cross at least one of the -10 or 10 bounds, with 17 of the 19 crossing the upper bound of 10. This result implies a trend for higher CIR values in the EN episodes, but with too much variance between EN episodes that no evidence of difference could be considered. Except for site 31, the largest variation in Group 3 was for sites with codes between 30 and 40, all located in the north of Minas Gerais and south of Bahia, between 12° S and 17° S, in the most northern areas of coffee-growing region.

As mostly of the confidence interval bars are placed above the -10 bound and crossing above the 10 bound, there is a trend of higher CIR during EN conditions than during LN, although it is highly variable among sites (Figure 2). Due to these large variations, 19 of the sites exhibit no evidence of difference, which means a very large difference poorly known. It means that the differences of CIR between EN and LN is too large inside each ENSO episode that they cannot be separated.

5.4. Discussion

5.4.1. ENSO effects on coffee leaf rust infection rates

The results obtained in this study (Figures 2 and 3) suggest that the ENSO phenomenon have minor impact on CLR risk between 12° S and 17° S latitudes and east of 52° W longitude in Brazil, similar to suggested by Ropelewski and Halpert (1987). The sites with differences of CIR between EN and LN episodes (Group 1) are placed on the South/Southeast region of the country, requiring more attention with CLR control during EN seasons. EN seasons occurred in 20 of the 65 analyzed seasons, while LN was only present in 16 seasons. This predominance of EN effect on CIR affects coffee growers in Paraná state in approximately one of three seasons. Based on this information, the number of sprays in the field can be determined in advance once EN is prognosticated. The regular CLR control in coffee fields can be done with two sprays during the season or with three when weather conditions are highly favorable. Another management practice that can be adopted is to regulate the chemical doses for the sprays. In ENSO episodes, under favorable conditions for CLR occurrence in the season, the recommended doses of 0.5 L ha^{-1} can be adjusted for 0.75

L ha^{-1} (AGROFIT 2017), which will perform differently in terms of residual period (for different products the doses can change, however the effect on the residual has the same trend). In the same way, the timing of the sprays can be improved by using a disease warning system, resulting in better CLR control.

The minor impact of the ENSO phenomenon on coffee leaf rust epidemic in the majority of the producing regions of Brazil is because the main growing areas are located in the south of Minas Gerais state (around 22 ºS), where evidence of no difference between EN and LN episodes (Group 2) is predominant. This happens because this specific region is located in a transition area with low influence of ENSO. In Brazil, the region with more influence of ENSO on climate variability is located at the north of 8º S and at the south of 25º S (Ropelewski and Halpert 1987).

Even in EN seasons, for the regions with influence of this phenomenon on plant disease, exceptions are possible. The study of Del Ponte et al. (2011), found differences for EN-LN episodes for soybean rust, presenting higher favorability to the pathogen on EN seasons. However, in the weak EN of 2004-05 in Rio Grande do Sul state (around 28 ºS), the weather was unfavorable to soybean rust epidemic.

In all the eight sites with evidence of difference of CIR between EN and LN seasons (Group 1), EN seasons showed more favorability for CIR than during LN seasons. Six of these eight sites are located in the Southern part of Brazil, where EN normally results in above average minimum temperature and rainfall (Berlato and Fontana 2003; Marengo and Camargo 2008), exactly the opposite of what is observed in the Northeast Brazil (Pezzi and Cavalcanti 2001; Berlato and Fontana 2003).

In these six sites, it is recommended to have more attention for CLR control during EN seasons. The other two sites of Group 1 (Araxá, MG, and Itamarandiba, MG) are isolated and considered as outliers, since they are in a transition area (Ropelewski and Halpert 1987; Coelho et al. 2002). Considering that, it is not clear that ENSO has the same impact on CLR as in the sites in the South, since ENSO use to have regional pattern of weather variation and not local or isolated pattern (Ropelewski and Halpert 1987; Pezzi and Cavalcanti 2001; Coelho et al. 2002; Berlato and Fontana 2003).

The sites in Group 3 present a large degree of variation of CLR during the ENSO phases which makes impossible to define presence or absence of effects of ENSO on disease epidemics. As the sites are not located on an area with no ENSO related signal for rainfall and temperature, the lack of influence on CLR would be expected (Ropelewski and Halpert 1987).

The region between 3 ºS and 17 ºS presents large interannual rainfall variation (Kousky and Chu 1978; Kousky 1979). As the latent and sensible heat balance is modified by the input of water in the environment (Lenters et al. 2011), probably the rainfall events result in changes of temperature and relative humidity. The variation of rainfall on the region can be as high as 300% (Kousky and Chu 1978), which is possibly the major CIR factor at this region and not ENSO phases. It explains the lack of evidence of differences of CIR between EN and LN episodes, and the large variation between seasons. The variability on rainfall in this region is mainly caused by cold fronts (Kousky and Chu 1978; Kousky 1979).

5.5. Final remarks

As far as we know, this is the first study analyzing ENSO effects using the confidence interval methodology, which allows us to summarize the differences between ENSO seasons of a large data series with multiple sites in a simple figure. This approach makes it possible for further long-term studies about ENSO impact on large areas. Possible analysis can be diseases measurements (e. g. area under disease progress curve, maximum intensity), and weather variables (e. g. air temperature, relative humidity, rainfall, solar radiation) under ENSO influence.

A successful tool that was previously used for the ENSO evaluation was a box-plot approach as shown in Del Ponte et al. (2011). Two special differences done it useful in their study. The study area covered Rio Grande do Sul state in Brazil, which is approximately 10 times smaller than the area presented in this research. Also, the predominance of a positive effect for soybean rust favorability was observed during EN seasons in the whole study area. Checking the differences between ENSO phases in larger data sets without this novel approach becomes tough when using large amount of information, as used in the present study. Box-plots for three ENSO phases and 45 sites would result in too many information, making interpretation difficult. To simplify the results, one graph and a map were used in this study. The graph is important for the visualization of CIR variation, and with the map we can visualize the spatial distribution of ENSO effects on CIR.

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