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Spatial distribution of Phoma leaf spot of coffee and relationship with environmental and host variables

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ABSTRACT

The objective of this study was to evaluate the spatial distribution of Phoma leaf spot of coffee and its relationship with the environmental variables altitude, soil texture, and mineral nutrients. In addition, the relationship between disease and foliar nutrients, leafing, and plant production was evaluated. The study was carried out in a 7.65 ha coffee plantation for two years. A total of 86 points were georeferenced in this area. The incidence and severity of the disease were assessed monthly, and the data were transformed into annual values of “Area Under the Incidence Progress Curve” (AUIPC) and “Area Under the Severity Progress Curve” (AUSPC) of the disease. Likewise, the monthly data for the leafing were transformed into annual values of “Area Under the Leafing Progress Curve” (AULPC). Environmental and host variables significantly correlated with the AUIPC were subjected to geostatistical modeling. Higher AUIPC and AUSPC were observed in the second year of the study. The altitude, P-rem and Ca present in the soil, as well as the P and N present in the leaves, showed a positive correlation with the AUIPC. The K, Cu, and Mn present in the leaves, the AULPC and the production were negatively correlated with this variable. The exponential semivariogram model was the most appropriate to model the spatial autocorrelation of the variables analyzed, except for altitude.

Keywords: *Coffea arabica L.,* Altitude, Geostatistics, Plant mineral nutrition.

Distribuição espacial da Mancha de *Phoma* do cafeeiro e relação com variáveis ambientais e do hospedeiro

RESUMO

O objetivo deste estudo foi avaliar a distribuição espacial da Mancha de Phoma do cafeeiro e sua relação com as variáveis ambientais altitude, textura do solo e nutrientes minerais. Além disso, foi avaliada a relação entre doenças e nutrientes foliares, enfolhamento e produção das plantas. O estudo foi realizado em cafezal de 7,65 ha durante dois anos. Foram georreferenciados 86 pontos nesta área. A incidência e a severidade da doença foram avaliadas mensalmente e os dados foram integrados em valores anuais de “Área Abaixo da Curva de Progresso da Incidência” (AACPI) e “Área Abaixo da Curva de Progresso da Severidade da doença” (AACPS). Da mesma forma, os dados mensais de enfolhamento foram transformados em valores anuais de “Área Abaixo da Curva de Progresso de Enfolhmaneto” (AACPE). Variáveis ambientais e do hospedeiro significativamente correlacionadas com a AACPI foram submetidas à modelagem geoestatística. Maiores AACPI e AACPS foram observados no segundo ano do estudo. A altitude, o P-rem e o Ca presentes no solo, bem como o P e o N presentes nas folhas, apresentaram correlação positiva com a AACPI. O K, Cu e Mn presentes nas folhas, a AACPS e a produção correlacionaram-se negativamente com esta variável. O modelo de semivariograma exponencial foi o mais adequado para modelar a autocorrelação espacial das variáveis analisadas, exceto a altitude.

Palavras-chave: *Coffea arabica* L., Altitude, Geoestatística, Nutrição mineral de plantas.

1. Introduction

Coffee is one of the main commodities traded worldwide, being the Brazil the largest producer and exporter, whereas the main importers are the European Union (EU) and the United States (USA) (Usda, 2023). The main species produced in Brazil is *Coffea arabica* L., with a production area of 1.48 million hectares in 2023 and more than 38.9 million 60-kg bags of green coffee processed (Conab, 2024), but the planted cultivars are susceptible to various diseases. These can reduce grain yield and quality and, in some cases, cause plant death (Matiello et al., 2016).

Among these diseases, Phoma leaf spot (*Phoma* spp.) stands out, which causes leaf lesions, death of branches, and mummification of flowers and fruits, reducing the coffee yield between 15 and 43% (Pozza et al., 2010). The progress of the disease is favored by temperatures between 15 and 20 °C and daily rainfall above 4 mm (Pozza and Alves, 2008; Santos et al., 2014; Lorenzetti et al., 2015). Phoma leaf spot has been found in regions with crops facing south, southeast, and east and exposed to strong and cold winds (Carvalho et al., 2013).

Regarding disease management, control is performed with the use of fungicides. However, these products are expensive and do not always show satisfactory results, as the pathogen can develop resistant populations. Therefore, the integration of other strategies is necessary, including the management of horizontal resistance using balanced fertilization. Nutrients supplied in appropriate amounts may increase the resistance of plants to pathogen infection (Huber et al., 2012). However, given the natural variability of the soil, nutrients are not present in soils homogeneously or according to crop requirements. This condition affects not only plant nutrition but also plant-pathogen interactions.

Therefore, understanding the nutrient spatial distribution is necessary, with the goal of managing soil fertility to increase yield and simultaneously make the plants more resistant. Thus, inputs can be applied at varied rates according to the needs of each plantation. In this sense, geostatistics can be used to model the spatial distribution of environmental variables and thus help define the best management strategies for reducing phytosanitary problems. Therefore, the objective of this study was to study the spatial distribution of Phoma leaf spot and its relationship with environmental and host variables.

2. Material and Methods

The experiment was conducted for two years in a commercial plantation belonging to “NKG Fazendas Brasileiras Ltda”, located in the Santo Antônio do Amparo municipality, Minas Gerais state, Brazil. The geographical coordinates of the reference point are latitude 20°53'23.7" S, longitude 44°52'56.9" W, and altitude of 1,145.9 m. The area had 7.65 ha and was planted with the *Coffea arabica* L. cultivar Catucaí amarelo 2 SL, four years old, susceptible to Phoma leaf spot and at 3.7 x 0.7 m spacing. A regular grid was delimited in the 7.65 ha area with 86 points and with 30 x 30 m between points for performance of the geostatistical evaluations (Figure 1). These points were georeferenced using a Topcon® Hiper Lite L1 L2 GNSS receiver. Each georeferenced sampling point consisted of five coffee plants, with three plants in the same row, one above and the other below the center row.

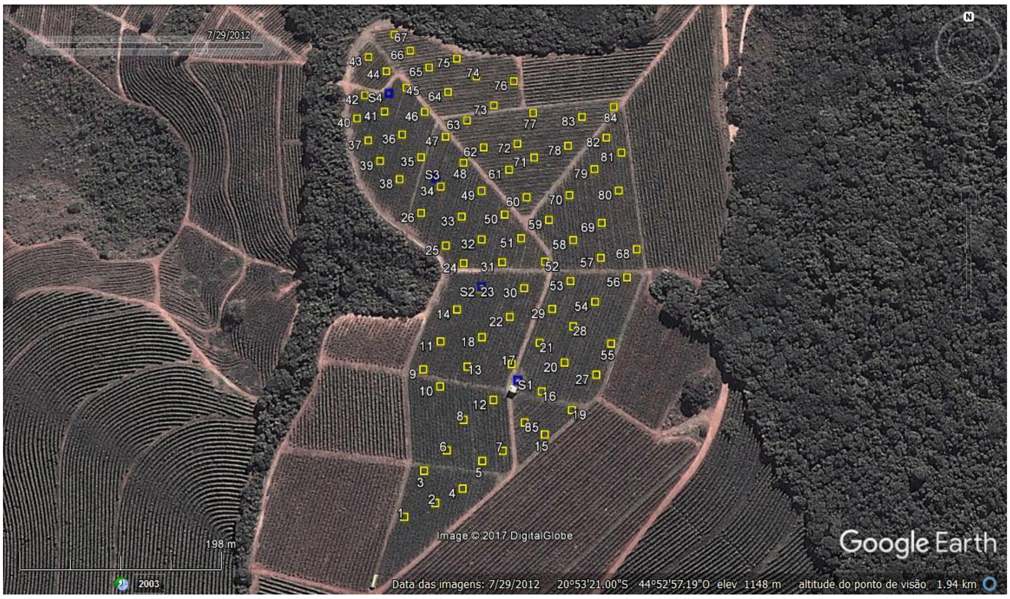

Figure 1. Satellite image of the experimental area. “NKG Fazendas Brasileiras Ltda”, Santo Antônio do Amparo, MG, 2014 (Google Earth, 2014) and grid of georeferenced points. S1 (blue) indicates the site of the Datalogger CR1000 automatic station, manufactured by Campbell Scientific Inc.®

Monthly assessments of the incidence and severity of the Phoma leaf spot were performed, from September 2013 to August 2015. The progress curves of disease incidence and severity were constructed with this information on the monthly mean of the 86 georeferenced points. In each plant, the first pair of fully expanded leaves of four branches in the upper third of the canopy was randomly evaluated, with two branches on each exposure side, totaling eight leaves per plant and 40 leaves per georeferenced point. In each month, 40 leaves were randomly sampled per georeferenced point, as previously described. The disease incidence data at each georeferenced point were obtained dividing the number of diseased leaves by the total number of leaves, multiplied by 100 (Madden et al., 2007). Severity was assessed using the diagrammatic scale developed by Salgado et al. (2009).

Monthly data on disease incidence and severity at each georeferenced point were individually converted into annual values of "Area Under the Incidence Progress Curve" (AUIPC) and "Area Under the Severity Progress Curve" (AUSPC) using Equation 1, according to Shaner and Finney (1977). Thus, were obtained the AUIPC and AUSPC values for 2013/14 and 2014/15.

$$AUDPC = \sum_{i=1}^{n-1} \left(\frac{y_i + y_{i+1}}{2}\right)(t_{i+1} - t_i) \qquad (1)$$

Where:

$AUDPC$ = Refers to the AUIPC or AUSPC;

y_i = disease proportion at *i-th* observation;

t_i = time, in days, in the *i-th* observation;

n = total number of observations.

Leafing was also evaluated monthly at each georeferenced point using a diagrammatic scale. Subsequently, the data were converted into annual values of "Area Under the Leafing Progress Curve" (AULPC), using the same reasoning presented in the previous equation.

To evaluate the physicochemical characteristics of the soil and the mineral nutrition of the plants, soil and leaf samples were collected annually in January 2014 and 2015, at each georeferenced point. Were determined the soil fertility and texture, according to the recommendations of the Soil Fertility Commission of Minas Gerais (Ribeiro et al., 1999). For nutritional status of the plants, leaf samples were collected randomly in the middle third of the canopy, according to Ribeiro et al. (1999), totaling eight leaves per plant and 40 leaves per point. In the laboratory, were determined the levels of the mineral nutrients N, P, K, Ca, Mg, S, B, Cu, Mn, Zn, Fe, and Mo, according to Malavolta et al. (1997).

In each agricultural year, fruit production was also measured. The results were expressed as the mean fresh fruit weight per plant, i.e., the average production of the five plants at each georeferenced point. An automatic weather station was installed in the plantation at an elevation of 1,145 m and used a CR1000 Datalogger from Campbell Scientific Inc.® (Figure 1). The mean air temperature, and cumulative rainfall were obtained for 30 days prior to each monthly evaluation of the disease.

The applications of soil amendments, fertilizers and products to control pests and other diseases were performed according to the crop requirements and while considering the total area as homogeneous, with the same management being carried out in all plots of this experiment. The correlation between environmental and host variables with Phoma leaf spot was evaluated by Pearson's correlation analysis ($p \leq 0.05$), using the statistical software "Statistica" (StatSoft, 2004).

The AUIPC data were analyzed by geostatistical modeling to study the spatial autocorrelation. The environmental and host variables that were correlated simultaneously with the AUIPC and months of highest disease incidence in each agricultural year were also modeled. In the geostatistical analyses, the presence of autocorrelation in the variables was checked using semivariograms (Yamamoto and Landim, 2013). The semivariance was calculated with Equation 2.

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i + h) - Z(x_i)]^2 \qquad (2)$$

Where:

$\gamma(h)$: estimated semivariance;

$N(h)$: number of pairs of measured values;

$Z(x_i + h)$ and $Z(x_i)$ are vectors separated by a distance h.

When autocorrelation was observed, three isotropic models were fit to the data: spherical, exponential and Gaussian models (Equations 3, 4, and 5).

Spherical Model:

$$\begin{cases} \gamma(h) = C_0 + C_1\left[1.5\frac{h}{a} - 0.5\left(\frac{h}{a}\right)^3\right] & for\ h < a \\ \gamma(h) = C_0 + C_1 & for\ h \geq a \end{cases} \qquad (3)$$

Exponential Model:

$$\gamma(h) = C_0 + C_1\left[1 - \exp\left(-\frac{h}{a}\right)\right] \qquad (4)$$

Gaussian Model:

$$\gamma(h) = C_0 + C_1\left[1 - \exp\left(-\left(\frac{h}{a}\right)^2\right)\right] \qquad (5)$$

Where

C_0: nugget effect;

C_1: contribution;

a: range;

h: distance between pairs of points.

The selection of models was performed according to the self-validation criteria, using the mean error closer to 0 (Equation 6) and root mean square standardized error closer to 1 (Equation 7) (Webster and Oliver, 1992; Oliver and Webster, 2007).

$$ME = \frac{1}{N}\sum_{i=1}^{N}[\hat{Z}(x_i) - Z(x_i)] \quad (6)$$

$$RMSSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\frac{\hat{Z}(x_i) - Z(x_i)}{\sigma^2(x_i)}\right]^2} \quad (7)$$

Where:

ME: mean error;

RMSSE: root mean square standardized error;

N: number of observations;

$\hat{Z}(x_i)$: estimated kriging;

$Z(x_i)$: observed value at location x_i and σ^2 is the kriging variance.

The degree of spatial dependence (DSD) was calculated (Equation 8). The semivariograms with nugget effect (C_0) of up to 25%, between 25 and 75%, and above 75% of the plateau were considered to have strong, moderate, and weak spatial dependence, respectively (Cambardella et al., 1994).

$$DSD = \left(\frac{C_0}{C_0 + C_1}\right) \text{x } 100 \quad (8)$$

Finally, the data were interpolated using ordinary kriging (Equation 9), and maps were generated to interpret the spatial behavior of each variable. Geostatistical analyses were performed using the ArcGis 10.1 software (ArcGIS, 2012).

$$\begin{cases} \sum_{j=1}^{n} \lambda_j \gamma(x_i - x_j) - \alpha = \gamma(x_i - x_0) \ for\ i = 1, \ldots, n \\ \sum_{j=1}^{n} \lambda_j = 1 \end{cases} \quad (9)$$

Where:

$\gamma(x_i, x_j)$ and $\gamma(x_i, x_0)$ are, respectively, the semivariance between points x_i and x_j and between points x_i and x_0;

α: Lagrange multiplier.

3. Results and Discussion

The Phoma leaf spot incidence and severity progress curves had several peaks in each agricultural year (Figure 2A and 2B). In the period from September 2013 to August 2014, these peaks were observed in October and December 2013 and in June and August 2014. In the second agricultural year, the disease continued to display an increasing trend in September 2014, with a smaller peak in November 2014 and two other higher peaks in February and May 2015 (Figure 2a and 2b). In general, the highest disease intensities occurred at mean temperatures below 20 °C, and in periods with greater precipitation (Figure 2). The higher volumes of precipitation in 2014/15, associated with greater plant leafing, may have contributed to the higher AUIPC and AUSPC values (Table 1). However, in this agricultural year a higher average production was observed.

A significant positive correlation was observed between the AUIPC and AUSPC data in both years studied, with values of 0.70 in the agricultural year 2013/14 and 0.94 in 2014/15. Therefore, Phoma leaf spot incidence in the form of AUIPC was chosen to assess the relationship of this disease with environmental and host variables, as it is an easily measured variable, and as it well reflects the severity behavior of this disease under field conditions.

For the 2013/14 period, the correlation of environmental and host variables with the disease incidence was analyzed in the months of December 2013 and in May and August 2014, while the correlations in the following year (2014/15) were analyzed for the months of September 2014 and February and May 2015 (Table 2). These months were chosen because they showed a high incidence of the disease (Figure 2A). In addition, the variables presented below (Table 2) were selected because they had a significant correlation with at least two of the three months mentioned above, in addition to a significant correlation with the AUIPC in each period.

In 2013/14, the disease was positively correlated with altitude and leaf P, while AULPC and production were negatively correlated (Table 2). In 2014/15, the disease again correlated positively with altitude, and with the soil attributes Ca and remaining phosphorus (P-rem). In relation to foliar nutrients, N showed a positive correlation, while K, Cu and Mn were negatively correlated (Table 2). Geostatistical studies were conducted to model the spatial distribution of AUIPC 2013/14 and 2014/15 and to model the environmental and host variables mentioned above (Table 2), since they were correlated with the disease according to the criteria already described.

In Table 2, the classical theoretical models were fitted to the semivariograms of the variables with structured point clouds, that is, with an indication of spatial dependence (C_1) via graphical analysis (data not shown). The leaf contents of P in 2013/14 and N in 2014/15, although significantly correlated with AUIPC, did not show spatial autocorrelation; that is, the samples of each variable did not present spatial dependence among themselves. The same was observed for AULPC in 2013/14.

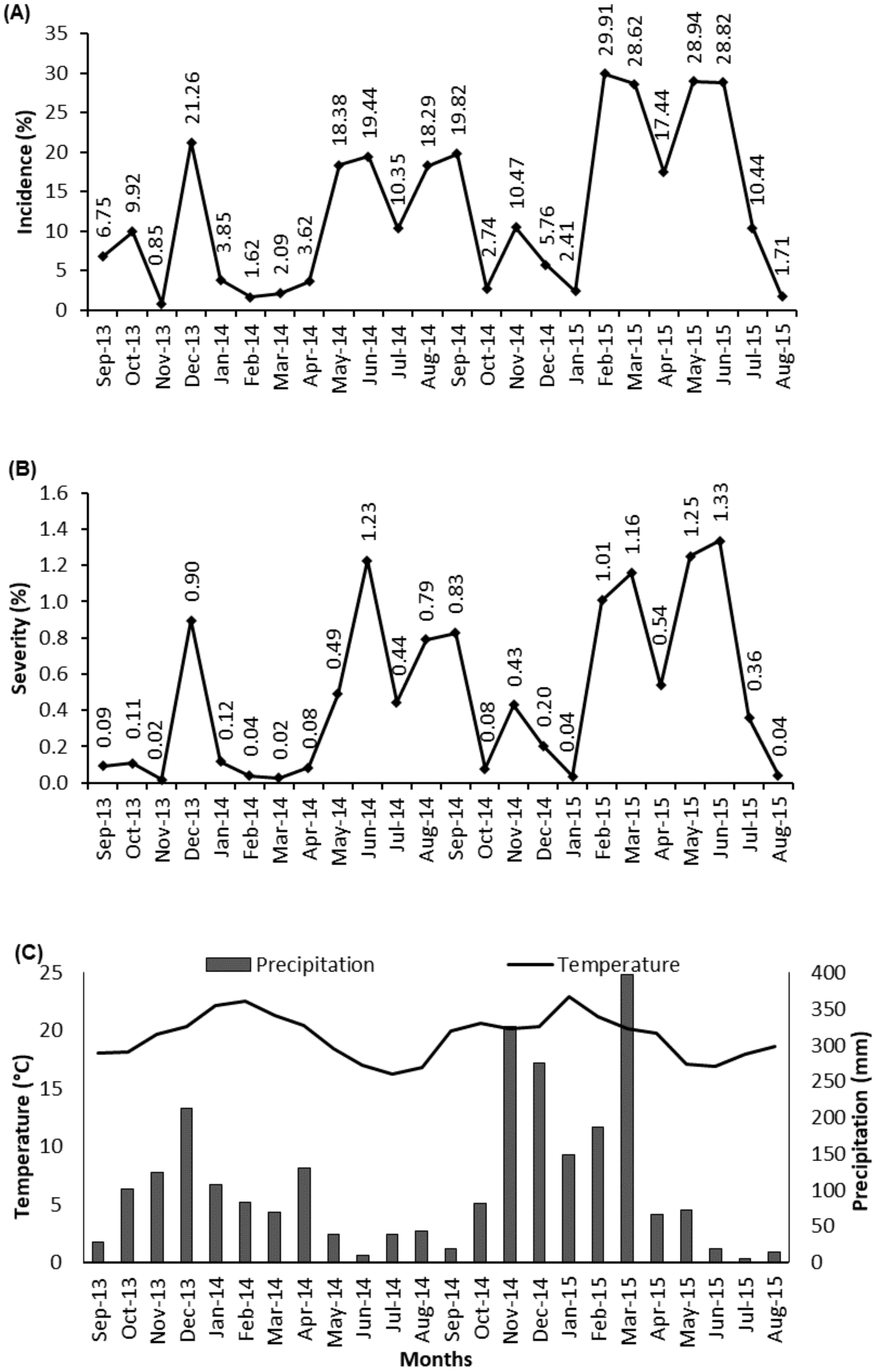

Figure 2. Phoma leaf spot (A) incidence and (B) severity progress curves and (C) mean air temperature (°C), and cumulative rainfall (mm) in the 30 days prior to each monthly disease assessment.

Table 1. Mean values of the "Area Under the Incidence Progress Curve" (AUIPC) and "Area Under the Severity Progress Curve" (AUSPC) of the disease, "Area Under the Leafing Progress Curve"' (AULPC), and fruit yield (kg.plant^{-1}) in 2013/14 and 2014/15.

Period	AUIPC	AUSPC	AULPC	Production (kg.plant^{-11})
2013/14	3,175.21	121.54	22,511.46	3.42
2014/15	5,284.66	204.72	23,625.77	4.47

Thus, these variables were not subjected to kriging analysis. The aforementioned mean of leaf N and P were 3.00 dag.kg^{-1} and 0.14 dag.kg^{-1}, respectively, while the mean of AULPC was 22,511.46 (dimensionless). Based on the self-validation criteria, the exponential model was the most suitable for modeling all the studied variables, except for altitude, with mean error closer to 0 and root mean square standardized error closer to 1. For altitude, the model with the best results for these estimates was the spherical model (Table 3).

In 2013/14, the AUIPC had a moderate DSD value, and a strong value in 2014/15 (Table 3). The range of the disease in the form of AUIPC was 96.82 m in 2013/14; that is, a single infected plant can contribute to spreading the disease within a radius of 96.82 m. In 2014/15, an increase in range to 162.35 m was indicated, given the environmental conditions favorable to the progress of the disease in this period. Regarding AUIPC values in the area, in the first agricultural year, the thresholds ranged from 737.08 to 5,654.58, while in the second year, they ranged from 991.25 to 9.572.50 (Figure 3a and 3b).

Table 2. Results of correlation analysis of values of monthly incidence and "Area Under the Incidence Progress Curve" (AUIPC) 2013/14 and 2014/15 with the environmental and host variables.

	December 2013	May 2014	August 2014	AUIPC 2013/14
		Soil atributes		
Altitude (m)	0.64*	0.49*	0.31*	0.60*
		Host variables		
P (dag.kg^{-1})	0.41*	0.28*	0.42*	0.30*
AULPC	-0.38*	-0.31*	-0.17^{ns}	-0.24*
Production (kg.plant^{-1})	-0.53*	-0.45*	0.17^{ns}	-0.29*
	September 2014	February 2015	May 2015	AUIPC 2014/15
		Soil atributes		
Altitude (m)	0.41*	0.69*	0.28*	0.74*
Ca (cmol.dm^{-3})	0.29*	0.20^{ns}	0.23*	0.32*
P-rem (mg.L^{-1})	0.12^{ns}	0.27*	0.42*	0.27*
		Host variables		
N (dag.kg^{-1})	0.26*	0.36*	0.02^{ns}	0.35*
K (dag.kg^{-1})	-0.09^{ns}	-0.23*	-0.32*	-0.28*
Cu (mg.kg^{-1})	-0.16^{ns}	-0.29*	-0.31*	-0.38*
Mn (mg.kg^{-1})	-0.01^{ns}	-0.23*	-0.30*	-0.23*

*Significant correlation ($p \leq 0.05$). ^{ns} Not significant.

Table 3. Selected models, estimates of the parameters of the fitted isotropic semivariograms, and degree of spatial dependence (DSD) for the "Area Under the Incidence Progress Curve" (AUIPC) and for the environmental and host variables in 2013/14 and 2014/15.

Variables	Coefficients				DSD (%)
	Model	C_0	C_1	A_0 (m)	(C_0/C_0+C_1)x100
		2013/14			
AUIPC	EXP	199,829.20	550,987.20	96.82	26.61
Altitude (m)	SPH	0	2.52	128.54	0
Production (kg.planta^{-1})	EXP	0.95	0.32	126.41	74.80
		2014/15			
AUIPC	EXP	216,045.50	960,984.40	162.35	18.35
Ca (cmol.dm^{-3}) (soil)	EXP	0.21	0.25	174.18	45.65
P-rem (soil)	EXP	1.58	5.68	147.81	21.76
K (dag.kg^{-1}) (leaf)	EXP	0	0.88	70.32	0
Cu (mg.kg^{-1}) (leaf)	EXP	0	86.35	71.28	0
Mn (mg.kg^{-1}) (leaf)	EXP	0	13,487.10	50.09	0

C_0: Nugget Effect; C_1: Contribution; A_0: Range. EXP: exponential; SPH: spherical.

The altitude showed the highest correlation with AUIPC (Table 2), with an increase in AUIPC values of approximately 199.68 units for each meter of altitude, in the period 2013/14. In 2014/15, this relation was approximately 348.45 units (Figure 3a and 3b). Regarding the mineral nutrients present in the soil, the Ca showed moderate DSD, whereas the P-rem had strong DSD (Table 3). The range of these nutrients was 174.18 and 147.81 m, respectively. The soil Ca thresholds ranged from 0.41 to 5.05 cmol.dm^{-3}, while the P-rem thresholds ranged from 2.63 to 19.14 mg.L^{-1} (Figure 3d and 3e).

The K, Cu, and Mn present in the leaves showed strong DSD, with a nugget effect of zero for the semivariograms of these three nutrients. They also had the smallest ranges when compared with the other variables studied, with values of 70.32 m for K, 71.28 m for Cu, and 50.09 m for Mn (Table 3). Regarding the levels of these nutrients in the leaves, the K ranged from 1.71 to 5.34 dag.kg^{-1} (Figure 4c), while the Cu and Mn ranged from 12 to 55 and from 66 to 861 mg.kg^{-1}, respectively (Figure 4d and 4e). The semivariogram model fitted to the fruit production data in 2013/14 showed moderate DSD (Table 3), and the production in the plantation ranged between 0.07 and 6.63 kg.plant^{-1} (Figure 4f)

Phoma leaf spot showed irregular temporal progress, with greater intensity in 2014/15. Nevertheless, in that year, there was a higher mean production, 4.47 kg.plant^{-1} vs. 3.42 kg.plant^{-1} in 2013/14. This can be explained by the greater leafing in the form of AULPC, 23,625.77 in 2014/15 compared to 22,511.46 in 2013/14 (Table 1), providing a greater supply of photoassimilates to the plants, thus compensating for the higher values of incidence and severity recorded.

The AUIPC showed spatial autocorrelation between the points sampled, reaching 96.82 m in 2013/14 and 162.35 m in 2014/15; that is, a single infected plant can contribute to the dissemination of the disease in a radius of 96.82, and 162.35 m, respectively. The greater precipitation in 2014/15, associated with greater plant leafing, may have created a microclimate more favorable to the production and dispersion of the inoculum.

The AUIPC had a significant positive correlation with altitude, both in 2013/14 and in 2014/15. This is because at higher altitudes, the plantation is more exposed to adverse weather conditions, such as cold winds from the south (Carvalho et al., 2013). In such circumstances, the friction between leaves due to the wind can cause injuries, especially in young leaves, where infections occur. In fact, in field conditions, the infections always occur in the first or second pair of leaves, that is, young tissue. Firman (1965) observed the development of disease symptoms only in young leaves artificially injured before pathogen inoculation.

Additionally, temperatures between 15 and 20 °C favor fungal germ tube growth, increasing the chances of infection, even in times of low rainfall (Santos et al., 2014; Lorenzetti et al., 2015). Pozza and Alves (2008) reported temperatures between 16 and 20 °C combined with mean daily precipitation above 4 mm to be conditions highly favorable to Phoma leaf spot.

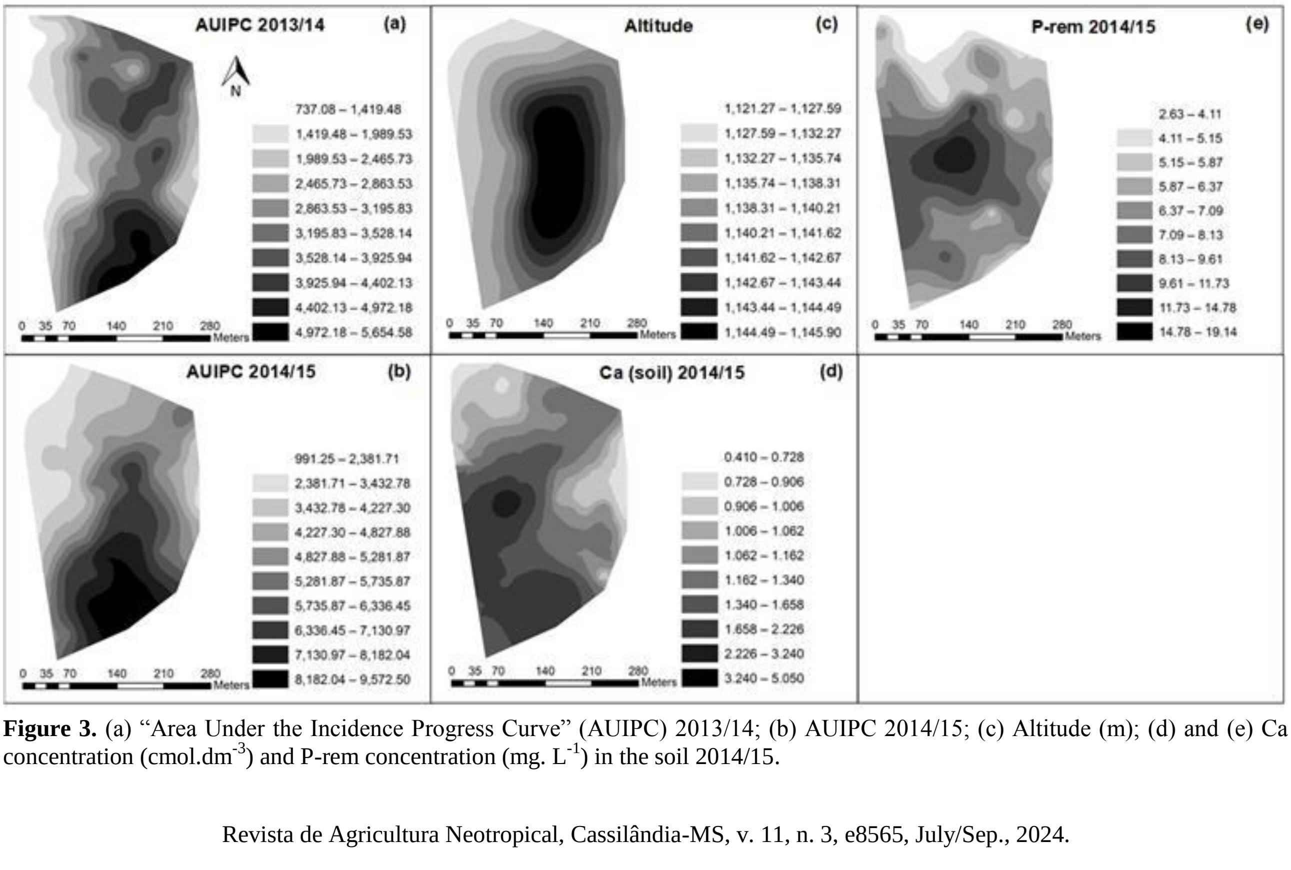

Figure 3. (a) “Area Under the Incidence Progress Curve” (AUIPC) 2013/14; (b) AUIPC 2014/15; (c) Altitude (m); (d) and (e) Ca concentration (cmol.dm^{-3}) and P-rem concentration (mg. L^{-1}) in the soil 2014/15.

In other words, even with low volumes of precipitation, sufficient to cause leaf wetness, within this temperature range, they can be associated with epidemic outbreaks. Regarding soil nutrients, the range provided by fitted models can help define areas of greater or lesser spatial distribution of these nutrients, and thus the generated kriging maps allow managing the soil according to its spatial variability, with adjustment of the application rate of soil amendments and fertilizers according to the crop requirements. In the case of leaf nutrients, the kriging maps generated with these data allow determining the nutritional status of the crop in different locations and associating this information with the spatial distribution of diseases.

Soil Ca was positively correlated with the disease in the 2014/15 period. However, for this nutrient, an antagonistic correlation is expected. This is because it may confer greater resistance to pathogen infection because of its structural function, forming calcium pectate in the middle lamella of the cell wall, a physical barrier to the development of pathogens (Huber et al., 2012; Taiz and Zeiger, 2013). In the present case, the Ca under analysis was only that of the soil, as leaf Ca did not correlate significantly with the disease, making the interpretation of the results difficult. In fact, the maps show a higher concentration of foliar K in the northern position of the area, as well as foliar Cu and Mn (Figure 4), being all these nutrients involved in plant resistance mechanisms against pathogens (Marschner, 2012). Thus, the higher concentrations of these nutrients may have acted together to inhibit the progress of the disease, despite the lower concentrations of Ca in the soil in this position in the area.

P-rem and leaf P and N presented positive correlations with the disease. P is essential in the formation of new organs, such as leaves and branches (Hawkesford et al., 2012). The function of P as a component of macromolecular structures is more significant in nucleic acids. In both DNA and RNA, phosphate bonds to ribonucleoside units to form macromolecules. Considering the total P bound to organic compounds, the fraction of this total used for the synthesis of ribonucleic acid differs between tissues and cells, being higher in young leaves, which require a greater amount of ribosomal RNA for fast protein synthesis, lower in mature leaves and very low in senescent leaves (Suzuki et al., 2001).

Thus, plants with adequate nutrient supply present greater formation of young leaves, which are more susceptible to Phoma leaf spot, thus explaining the observed relationships. N is the element required in highest quantities, and it plays a central role in plant metabolism as a constituent of proteins, nucleic acids, chlorophyll, coenzymes, phytohormones and secondary metabolites (Hawkesford et al., 2012). Therefore, the supply of N also contributes to young tissues, but if supplied in large quantities, it causes a dilution effect on the other nutrients. In addition, excess N reduces the production of lignin, phytoalexins, and tannins (Huber and Thompson, 2007). Consequently, the plants become more succulent due to the lower lignification of the tissues and, thus, are more predisposed to infection by pathogens.

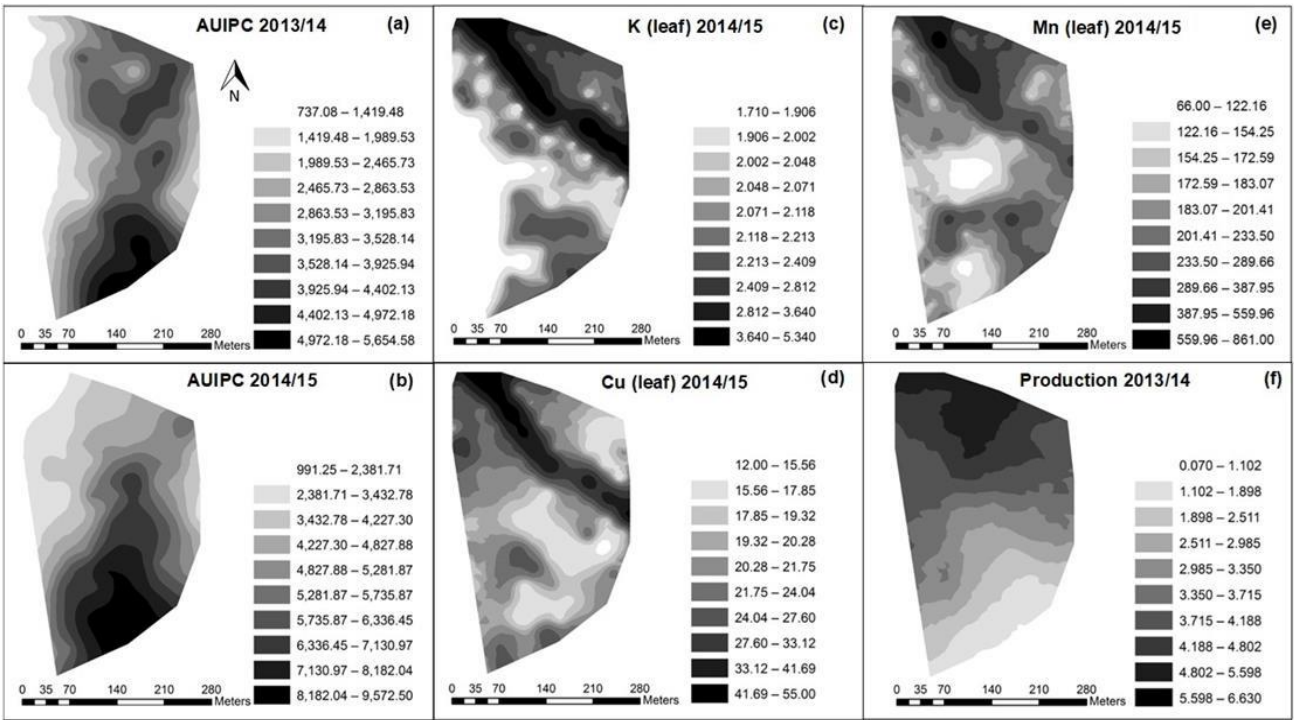

Figure 4. (a) “Area Under the Incidence Progress Curve” (AUIPC) 2013/14; (b) AUIPC 2014/15; (c) K levels in leaves 2014/15 (dag.kg^{-1}); (d) and (e) Cu and Mn content in leaf 2014/15 (mg.kg^{-1}) and (f) Fruit production 2013/14 (kg.plant^{-1}).

Lima et al. (2010) studied the relationship between the N and K supply via nutrient solution with the Phoma leaf spot in coffee seedlings and observed a linear increase of the AUIPC and AUSPC with the increase in N concentration, which agrees with the observations made in this study. Leaf K was negatively correlated with the disease, in agreement with the observations made by Lima et al. (2010) in the same study mentioned above. This macronutrient is essential for protein synthesis because, although it is not part of any molecule (because it has no constitutive function), it activates the enzymes involved in this process (Hawkesford et al., 2012).

Thus, the lack of K will result in the accumulation of sugars and amino acids in the leaves (Huber et al., 2012), which will not be converted into structural polysaccharides and proteins, respectively, making the plants more susceptible to the disease. In addition, these monomers will be readily available for assimilation and use by pathogens. Leaf Cu and Mn exhibited a negative correlation with the AUIPC. The Cu is a cofactor of enzymes related to photosynthesis and respiration (Broadley et al., 2012). Thus, its deficiency causes disturbances in plant metabolism, indirectly predisposing plants to attack by pathogens.

Of the various plant defense mechanisms, those related to phenols and lignins are the best known, and Cu, as well as Mn, plays key roles in the synthesis of these compounds (Broadley et al., 2012). Therefore, plants deficient in Cu and Mn have less accumulation of these substances and thus are more predisposed to the occurrence of the disease. Given the results of this study, a need exists for soil management and management of the mineral nutrition of plants that considers the spatial variability of nutrients. Thus, the application of soil amendments and fertilizers at a variable rate can contribute to maximizing yield and, at the same time, serve as an integrated tool in the management of Phoma leaf spot.

4. Conclusions

The Phoma leaf spot of coffee presents temporal variation in intensity, influenced by meteorological conditions, with monthly incidence averages varying from 0.85 to 29.91%. The disease presents spatial variation in intensity, influenced by altitude and nutrients N, P, K, Ca, Cu and Mn. The disease and the correlated environmental and host variables present a spatial dependence structure, except foliage, leaf N and P, and fit to the exponential semivariogram model, except altitude.

Authors' Contribution

Humberson Rocha Silva and Edson Ampélio Pozza wrote the main manuscript text. Humberson Rocha Silva, Aurivan Soares de Freitas, Marcelo Loran de Oliveira Freitas, and Mauro Peraro Barbosa Junior performed monthly disease assessments over the 24 months, under field conditions. Marcelo de Carvalho Alves collaborated in the data analysis. All authors reviewed the manuscript.

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