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# Use of Geostatistics as a Tool to Study Spatial-Temporal Dynamics of *Leucoptera coffeella* in Coffee Crops

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**Abstract:** Coffee is considered one of the most important commercial commodities globally, and in 2020, it moved to a global market of USD 102.02 billion. However, the attack of pests in coffee production can cause significant economic losses. *Leucoptera coffeella* is a critical pest in coffee-producing countries, with productivity losses reaching 87%. The knowledge of the spatial distribution patterns of *L. coffeella* is essential to developing an efficient sampling and control plan. Moreover, it allows us to target for control specific locations/seasons where *L. coffeella* occurrence is at its highest density before reaching the economic injury level. Therefore, our objective in this study was to determine the spatial distribution of *L. coffeella* in coffee crops through geostatistical analysis. Data on the population density of *L. coffeella* were collected over four years on a farm with 18 center pivots located in the Brazilian Cerrado. The presence of *L. coffeella* was recorded in all 18 pivots during the entire time of the study (2016 to 2020). The highest densities were from July to November. These high densities of *L. coffeella* positively correlated with maximum air temperatures and wind speed. It was also verified to negatively correlate with minimum air temperatures and rainfall. The surrounding vegetation does not affect the pest densities. The pest hotspots appeared in different pivots and different locations inside pivots. Furthermore, *L. coffeella* showed an aggregated distribution pattern. For three years, the colonization started at the edge of the crop. The sampling should be performed equidistant as the pest is distributed equally in all directions. The information found in this study provides valuable information to initiate timely management and control methods in coffee crops with a high incidence of *L. coffeella*, thus reducing production costs and the harmful effects of pesticide use.

**Keywords:** coffee leaf miner; geostatistics; integrated pest management; spatial distribution



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## 1. Introduction

Coffee is considered one of the largest commodities traded in the world, and it holds a significant share of global agribusiness [1–4]. Its production is of great economic and social importance in the countries where it is grown [2], representing a global market of USD 102.02 billion in 2020 [5]. However, the attack of pests in coffee production can cause great economic losses [2,6,7].

The coffee leafminer *Leucoptera coffeella* (Guérin-Méneville) (Lepidoptera: Lyonetiidae) is a critical pest in coffee-producing countries, especially in Neotropical regions [8–11]. This microlepidopteran causes damage in the immature phase due to feeding on the leaf parenchyma. This damage reduces the leaf area and photosynthetic capacity and occurs prematuration of leaves' senescence, leading to reductions in the yield and quality of the coffee berries [12]. Therefore, depending on the infestation levels of *L. coffeella*, productivity can decrease by around 50 to 87% [6,8,13,14].

The precise and correct management begins with the early detection of the *L. coffeella*, which can be made by determining the spatial distribution of pests and their dispersion patterns in the field [15–17]. This knowledge is vital since it allows us to carry out effective, low-cost, and environmentally friendly control measures [18,19].

Geostatistics is a tool that allows one to describe the dispersal patterns and the spatial distribution of pests in the field [19,20] (Martins et al., 2018; Rosado et al., 2015). This analysis uses the georeferenced sampled point for each location to provide the degree of dependence between samples, allowing us to make assumptions about the spatial distribution patterns of the pest in the field [18,21].

Despite the severe damage caused by *L. coffeella* to coffee crops, there are few studies about the decision-making process of whether or not to control this pest, especially considering its spatial distribution pattern. Thus, this research aimed to assess the spatioal-temporal distribution of *L. coffeella* in coffee crops. For this purpose, the spatial-temporal distribution of *L. coffeella* was monitored from April 2016 to February 2020 at 18 central pivots at Milan Farm, located in Bahia state, Northeast Brazil. The farm was located in one of the largest commercial coffee-producing regions in the Brazilian Cerrado.

## 2. Materials and Methods

### *2.1. Study Area*

Over four years (April 2016 to February 2020), this study was undertaken on Arabica coffee crops, red catuaí variety, at Milan Farm localized in Barreiras, Bahia, Brazil (45°30′29.44″ W, 12°18′16.04″ S) (Table 1 and Figure 1A). This region has a tropical climate with a dry season from May to September and a rainy season from October to April. The evaluated areas were located in the Cerrado biome and represent the locations with the highest attack intensities of *L. coffeella* in Brazil [6,9,22]. Eighteen central pivots of 100 hectares were assessed, with a total area of 1800 hectares. Figure 1B and Table 1 show the locations and characteristics of the 18 central pivots. The plant spacing in the assessed coffee crops was 3 × 1 m, and the sprinkler irrigation system was implemented via a central pivot. The application of the fungicides pyraclostrobin, thiophanate-methyl, azoxystrobin, and cyproconazole was used to control rust (*Hemileia vastatrix*), cercosporiosis (*Cercospora coffeicola*), and phoma spot (*Phoma costaricensis*); and the insecticides Abamectin, Thiamethoxam, Chlorantraniliprole, and Novalurom were also used. The same phytosanitary control management was assigned to all pivots.

**Table 1.** The geographical location of each pivot of the coffee plantation and the composition of the surrounding vegetation of each pivot.

| Pivots | Latitude | Longitude | Altitude (m) | Surrounding Vegetation | Surrounding Vegetation (%) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | North | East | South | West |
| 1 | 12°17′58.57″ S | 45°31′07.58″ W | 700 | PPA | 0.00 | 0.00 | 26.59 | 0.00 |
| | | | | Pasture | 9.08 | 9.08 | 9.08 | 9.08 |
| | | | | Coffee | 13.10 | 13.10 | 0.00 | 0.00 |
| | | | | Maize | 0.00 | 0.00 | 0.00 | 10.86 |
| 2 | 12°17′58.57″ S | 45°31′07.58″ W | 702 | PPA | 0.00 | 0.00 | 9.80 | 0.00 |
| | | | | Pasture | 15.99 | 15.99 | 15.99 | 15.99 |
| | | | | Coffee | 8.74 | 8.74 | 0.00 | 8.74 |
| 3 | 12°18′04.80″ S | 45°30′18.60″ W | 696 | PPA | 0.00 | 0.00 | 16.91 | 0.00 |
| | | | | Pasture | 25.37 | 25.37 | 0.00 | 25.37 |
| | | | | Coffee | 0.00 | 3.49 | 0.00 | 3.49 |

**Table 1.** *Cont.*

| Pivots | Latitude | Longitude | Altitude (m) | Surrounding Vegetation | Surrounding Vegetation (%) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | North | East | South | West |
| 4 | 12°18′00.75″ S | 45°28′59.25″ W | 696 | PPA | 0.00 | 11.00 | 0.00 | 0.00 |
| | | | | Pasture | 16.69 | 16.69 | 16.69 | 16.69 |
| | | | | Coffee | 7.41 | 7.41 | 0.00 | 7.41 |
| 5 | 12°16′55.60″ S | 45°31′05.79″ W | 725 | Cerrado | 0.71 | 0.00 | 0.00 | 0.00 |
| | | | | Pasture | 11.75 | 11.75 | 11.75 | 11.75 |
| | | | | Coffee | 12.69 | 12.69 | 12.69 | 0.00 |
| | | | | Maize | 0.00 | 0.00 | 0.00 | 14.20 |
| 6 | 12°17′15.25″ S | 45°30′32.71″ W | 724 | Pasture | 16.15 | 16.15 | 16.15 | 16.15 |
| | | | | Coffee | 8.85 | 8.85 | 8.85 | 8.85 |
| 7 | 12°16′58.77″ S | 45°29′57.72″ W | 726 | Pasture | 14.70 | 14.70 | 14.70 | 14.70 |
| | | | | Coffee | 10.30 | 10.30 | 10.30 | 10.30 |
| 8 | 12°17′26.68″ S | 45°29′21.76″ W | 716 | Pasture | 15.09 | 15.09 | 15.09 | 15.09 |
| | | | | Coffee | 9.91 | 9.91 | 9.91 | 9.91 |
| 9 | 12°17′29.59″ S | 45°28′37.66″ W | 696 | PPA | 0.00 | 0.00 | 12.89 | 0.00 |
| | | | | Pasture | 17.10 | 17.10 | 17.10 | 17.10 |
| | | | | Coffee | 9.35 | 9.35 | 0.00 | 0.00 |
| 10 | 12°16′58.13″ S | 45°28′34.46″ W | 719 | Pasture | 18.25 | 18.25 | 18.25 | 18.25 |
| | | | | Coffee | 6.75 | 0.00 | 13.50 | 6.75 |
| 11 | 12°16′35.41″ S | 45°29′02.14″ W | 723 | Pasture | 14.26 | 14.26 | 14.26 | 14.26 |
| | | | | Coffee | 14.32 | 0.00 | 14.32 | 14.32 |
| 12 | 12°16′15.61″ S | 45°29′43.01″ W | 738 | Pasture | 11.81 | 19.57 | 11.81 | 11.81 |
| | | | | Coffee | 14.25 | 2.25 | 14.25 | 14.25 |
| 13 | 12°16′37.66″ S | 45°30′29.57″ W | 738 | Pasture | 10.18 | 10.18 | 10.18 | 10.18 |
| | | | | Coffee | 14.82 | 14.82 | 14.82 | 14.82 |
| 14 | 12°16′36.74″ S | 45°30′43.78″ W | 733 | Cerrado | 0.00 | 21.74 | 0.00 | 0.00 |
| | | | | Pasture | 13.63 | 0.00 | 13.63 | 13.63 |
| | | | | Coffee | 12.02 | 12.02 | 12.02 | 0.00 |
| | | | | Maize | 0.00 | 0.00 | 1.31 | 0.00 |
| 15 | 12°16′05.13″ S | 45°30′37.98″ W | 741 | Cerrado | 7.60 | 0.00 | 0.00 | 7.60 |
| | | | | Pasture | 12.29 | 12.29 | 12.29 | 12.29 |
| | | | | Coffee | 0.00 | 17.82 | 17.82 | 0.00 |
| 16 | 12°15′49.18″ S | 45°30′03.91″ W | 740 | Cerrado | 18.82 | 0.00 | 0.00 | 0.00 |
| | | | | Pasture | 9.84 | 9.84 | 9.84 | 9.84 |
| | | | | Coffee | 0 | 13.94 | 13.94 | 13.94 |
| 17 | 12°15′56.03″ S | 45°29′26.17″ W | 741 | Cerrado | 13.91 | 0.00 | 0.00 | 0.00 |
| | | | | Pasture | 13.46 | 13.46 | 13.46 | 13.46 |
| | | | | Coffee | 0.00 | 10.75 | 10.75 | 10.75 |
| 18 | 12°16′05.79″ S | 45°28′41.41″ W | 740 | Cerrado | 8.43 | 0.00 | 0.00 | 0.00 |
| | | | | Pasture | 15.11 | 15.11 | 15.11 | 25.50 |
| | | | | Coffee | 0.00 | 0.00 | 10.36 | 10.36 |

Legend: PPA: permanent preservation area, Cerrado: the native biome vegetation.

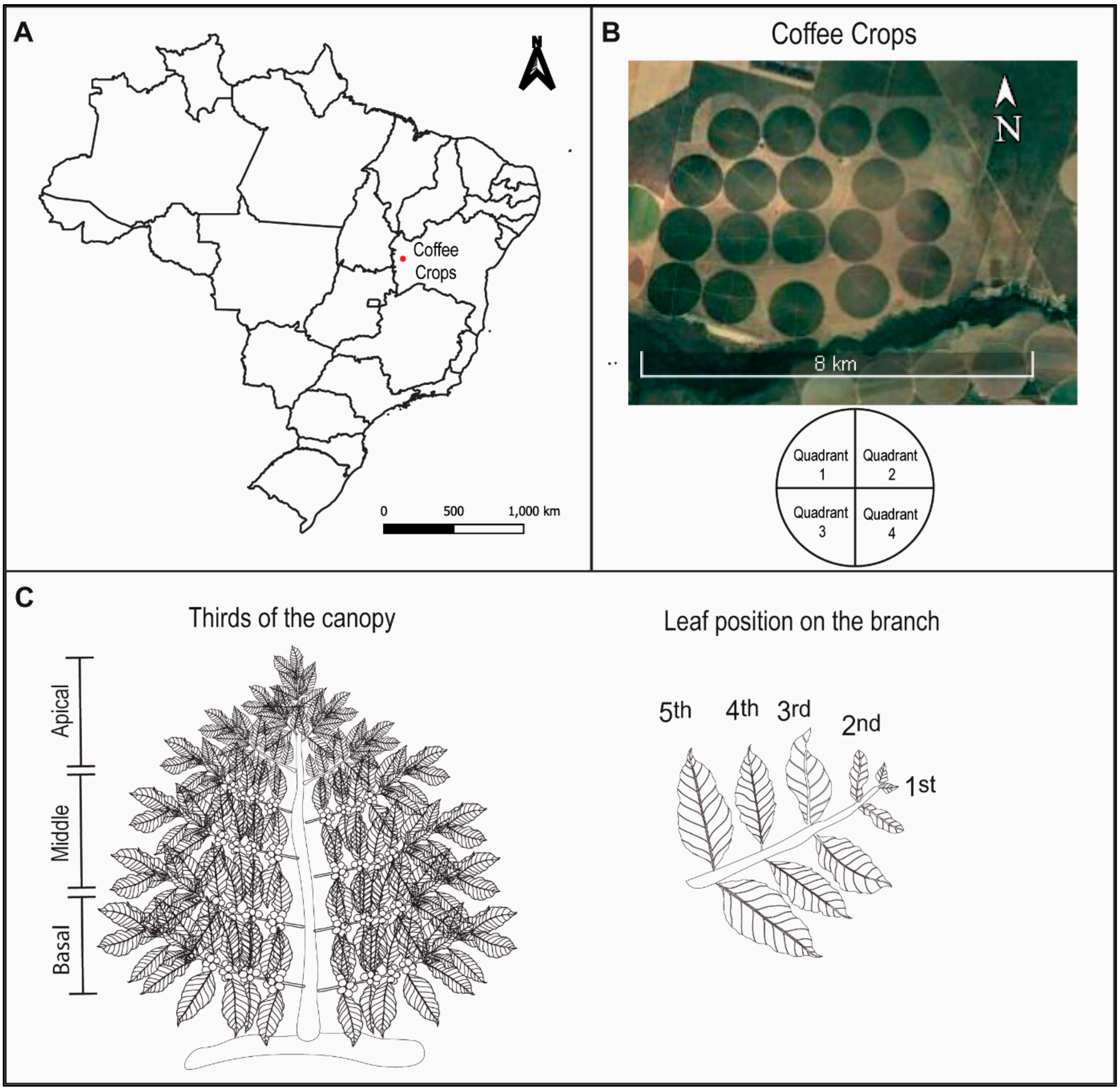


**Figure 1.** Location of coffee crops and leaf position evaluated in sampling. (**A**) Milan Farm location in Brazil; (**B**) pivot quadrants; and (**C**) leaf position where the attack of *Leucoptera coffeella* was evaluated in the thirds of the canopy and in the branches.

## 2.2. Data Collection

Data were collected from April 2016 to February 2020. The evaluations were carried out every two weeks at each central pivot. In these assessments, the area of each pivot was divided into four quadrants of 25 hectares. The center point of the quadrant of each pivot was georeferenced. In the central part of each of the quadrants, 25 randomly selected plants were evaluated (Figure 1B). Four leaves located equidistantly along the plant perimeter were evaluated in each plant. The leaf samples were collected in the median third of the canopy and from each branch's fourth pair of leaves (Figure 1C). These leaves were selected because they correlated with the total infestation of *L. coffeella* on coffee plants [12,23]. The presence or absence of active mines (i.e., mines with at least one *L. coffeella* larva feeding on the leaf parenchyma) was computed. Finally, the percentage of the *L. coffeella* mined leaves in each quadrant of the pivot was calculated. Therefore, the densities of *L. coffeella* in 72 georeferenced points in the 1800 hectares were calculated for each evaluation.

Additionally, we collected the climate variables data (temperature, rainfall, wind speed, and relative humidity) of the crop meteorological station of Milano Farm and the surrounding vegetation in each pivot of the Milan Farm data.

The radius of the pivot center (500 m) was measured, and an additional 500 m was added for a total of 1000 m from the pivot center for each pivot. This additional 500 m of the radius was measured to cover all vegetation around each pivot. Subsequently, the pivot area was discounted, and we calculated the percentage of vegetation around each pivot according to the size of the area in $m^2$. The vegetation types and percentages are described in Table 1. Areas were measured using satellite images from Google Earth Pro [24] (Figure 2).


**Figure 2.** Satellite images of the Milan Farm from Google Earth Pro. A radius of 1.000 m from the center of the pivot. The letter (P) and numbers indicate the pivot in the farm.

## 2.3. Statistical Analysis

### 2.3.1. Correlation Analysis

Correlation analysis using the PROC CORR procedure of the SAS [25] was used to investigate the correlation between *L. coffeella* density and the climatic variables (minimum and maximum air temperatures, rainfall, wind speed) and surrounding vegetation of the pivots.

### 2.3.2. Spatial Analysis

On each evaluation date, the percentages of leaves mined by *L. coffeella* in the 72 georeferenced points were submitted to geostatistical analysis using the software ArcGIS version 10.0 [26]. Initially, very discrepant data from the others (outliers) were removed to reduce errors in the semivariogram results and the interpolations [27,28].

Subsequently, semivariograms were estimated using circular, spherical, exponential, and Gaussian models. For each evaluation date, the selected model had a mean error value close to zero, a standardized error of the root mean square of the cross-validation curve close to one, and the smallest root means square error [29,30].

The presence of anisotropy was also tested for the following directions: 0°, 45°, 90°, and 135° directions. For each of these models, the nugget effect ($C_0$ = measure of sample error), sill (maximum value of semivariance in dependent samples), and range (A0 = distance beyond which there is no spatial correlation) were determined [31].

The range of spatial dependence (RSD) of each model was calculated using the following formula:

$$\mathrm{RSD} = \frac{C_0}{C_0 + C} \tag{1}$$

where $C_0$ = nugget effect, and C = contributione ($C_0$ + C) = still.

The spatial dependence of each semivariogram was classified as strong when RSD $\leq 0.25$, moderate when between 0.25 and 0.75, and weak when RSD > 0.75 [30,32].

The ordinary kriging method was used to interpolate and estimate the density of *L. coffeella* in the nonsampled pivot areas. Cross-validation was used to verify the quality of estimates obtained by the kriging models [19,30]. Using these estimates, interpolation maps were generated to visualize the spatial distribution of *L. coffeella* within fields.

## 3. Results

From the 188 tested models of the spatial distribution of *L. coffeella* in a coffee crop, 47 were selected. These 47 models were selected because they presented the lowest values of intercept (β0) and the sum of squared residue (RSS) and the highest coefficients of determination (R2) and slope of the curves of the models (β1). All 47 selected models showed plateau and nugget effect; 26 were spherical, 13 were Gaussian, 7 were exponential, and 1 was circular. From the 47 selected models, 45 showed strong spatial dependence (RSD < 0.25), and 2, moderate spatial dependence $0.25 \leq \mathrm{RSD} \leq 0.75$ (Table 2).

The ranges of the spatial dependence ranged from 891.58 m to 4974.43 m. From the 47 spatial distribution models of *L. coffeella*, 43 were isotropic, and 4 were anisotropic. The anisotropic models showed greater amplitude in the 56.43°, 56.18°, 18.98, and 136.76° directions (Table 2).

The presence of *L. coffeella* was observed in all 18 pivots during the entire year. The lowest densities of *L. coffeella* were detected from December to March, and the highest from July to November (Figures 3 and 4). From December to March, there were few areas in the pivots without the presence of the pest. During the times of highest densities of *L. coffeella* (i.e., July to November), there was a positive correlation between the insect densities, the maximum air temperatures (r = 0.13, t = 3.38, $p$ = 0.0004), and the wind speed (r = 0.10, t = 2.63, $p$ = 0.0044). In contrast, there was a negative correlation between the insect densities, the minimum air temperatures (r = −0.27, t = 7.77, $p$ = 0.0001), and the rainfall (r = −0.24, t = 6.53, $p$ = 0.0001). The effect of the surrounding vegetation on the pest densities was not detected (r = −0.03, t = 0.78, $p$ = 0.2179).

Even during the lower densities of *L. coffeella*, there were pivot sites where the pest densities were above the economic injury level, which we call pest hotspots hereafter. As the density of *L. coffeella* increased, the size of the pest hotspots also increased. In the different years of conducting this study, the pest hotspots appeared in different pivots and locations inside the studied area. In the first year, the pest hotspot initially appeared in the northeast region of the area. In the second and third years, the pest hotspot appeared in the area's eastern region (Figures 3 and 4), while in the fourth year, it appeared in the central area of the coffee crop (Figure 4).

**Table 2.** Characteristics of selected models for the spatial distribution of *Leucoptera coffeella* coffee.

| Date | Model | Anisotropy | Major Range (A0) | Minor Range (A0) | Direction (Degrees) | $C_0$ | C | Mean | RMSE | ME | RMSSE | ASE | RSD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/4/2016 | Spherical | No | 1775.56 | - | - | 0.00081 | 0.0185 | 0.0027 | 0.0904 | 0.0186 | 0.9999 | 0.0917 | 0.0420 |
| 1/5/2016 | Spherical | No | 1086.17 | - | - | 0.00000 | 0.0136 | 0.0053 | 0.1016 | 0.0387 | 1.0043 | 0.0999 | 0.0000 |
| 1/6/2016 | Spherical | No | 1481.13 | - | - | 0.00000 | 0.0163 | 0.0023 | 0.0889 | 0.0190 | 0.9926 | 0.0903 | 0.0000 |
| 1/7/2016 | Spherical | No | 1449.60 | - | - | 0.00201 | 0.0125 | 0.0013 | 0.0903 | 0.0144 | 1.0097 | 0.0899 | 0.1390 |
| 1/8/2016 | Spherical | No | 1382.90 | - | - | 0.00000 | 0.0127 | 0.0020 | 0.0825 | 0.0182 | 0.9782 | 0.0830 | 0.0000 |
| 1/9/2016 | Spherical | No | 1246.14 | - | - | 0.00000 | 0.0098 | 0.0010 | 0.0768 | 0.0089 | 1.0032 | 0.0776 | 0.0000 |
| 1/10/2016 | Spherical | Yes | 4452.01 | 1701.36 | 56.43 | 0.00449 | 0.0302 | 0.0001 | 0.1097 | 0.0031 | 1.0010 | 0.1113 | 0.1295 |
| 1/11/2016 | Spherical | Yes | 2663.02 | 891.58 | 58.18 | 0.00032 | 0.0103 | 0.0001 | 0.0707 | 0.0008 | 0.9920 | 0.0709 | 0.0303 |
| 1/12/2016 | Spherical | No | 891.58 | - | - | 0.00281 | 0.0066 | 0.0003 | 0.0826 | 0.0055 | 1.0038 | 0.0831 | 0.2997 |
| 1/1/2017 | Exponential | No | 4222.48 | - | - | 0.00002 | 0.0207 | 0.0010 | 0.0798 | 0.0067 | 1.0011 | 0.0814 | 0.0007 |
| 1/2/2017 | Spherical | No | 2389.14 | - | - | 0.00203 | 0.0316 | 0.0013 | 0.1058 | 0.0099 | 1.0012 | 1.0012 | 0.0603 |
| 1/3/2017 | Spherical | No | 1254.05 | - | - | 0.00000 | 0.0169 | 0.0012 | 0.1016 | 0.0021 | 1.0031 | 1.0031 | 0.0000 |
| 1/4/2017 | Exponential | No | 1583.42 | - | - | 0.00000 | 0.0073 | 0.0016 | 0.0738 | 0.0186 | 1.0083 | 0.0727 | 0.0000 |
| 1/5/2017 | Spherical | No | 1414.89 | - | - | 0.00000 | 0.0034 | 0.0034 | 0.0430 | 0.0108 | 1.0004 | 0.0426 | 0.0000 |
| 1/6/2017 | Gaussian | Yes | 1152.18 | 891.58 | 18.98 | 0.00000 | 0.0033 | 0.0256 | 0.0410 | 0.0256 | 1.0041 | 0.0409 | 0.0010 |
| 1/7/2017 | Exponential | Yes | 2051.51 | 1035.43 | 136.76 | 0.00000 | 0.0038 | 0.0009 | 0.0558 | 0.0135 | 1.0258 | 0.0534 | 0.0000 |
| 1/8/2017 | Spherical | No | 4974.43 | - | - | 0.00000 | 0.0367 | 0.0006 | 0.0705 | 0.0042 | 0.9716 | 0.0721 | 0.0000 |
| 1/9/2017 | Spherical | No | 4554.92 | - | - | 0.00687 | 0.0366 | 0.0008 | 0.1204 | 0.0051 | 1.0395 | 0.1146 | 0.1582 |
| 1/10/2017 | Circular | No | 1565.12 | - | - | 0.00000 | 0.0436 | 0.0003 | 0.1193 | 0.0047 | 0.9477 | 0.1280 | 0.0000 |
| 1/11/2017 | Exponential | No | 935.10 | - | - | 0.00000 | 0.0092 | 0.0008 | 0.0936 | 0.0048 | 0.9973 | 0.0943 | 0.0000 |
| 1/12/2017 | Gaussian | No | 4012.69 | - | - | 0.00196 | 0.0145 | 0.0005 | 0.0523 | 0.0101 | 1.0199 | 0.0505 | 0.1189 |
| 1/1/2018 | Gaussian | No | 3882.12 | - | - | 0.00093 | 0.0048 | 0.0008 | 0.0346 | 0.0183 | 0.9994 | 0.0343 | 0.1621 |
| 1/2/2018 | Gaussian | No | 1482.70 | - | - | 0.00059 | 0.0013 | 0.0001 | 0.0302 | 0.0056 | 1.0005 | 0.0305 | 0.3054 |
| 1/3/2018 | Gaussian | No | 1796.67 | - | - | 0.00119 | 0.0053 | 0.0000 | 0.0450 | 0.0047 | 1.0177 | 0.0458 | 0.1837 |
| 1/4/2018 | Gaussian | No | 2266.36 | - | - | 0.00153 | 0.0109 | 0.0005 | 0.0489 | 0.0054 | 1.0062 | 0.0499 | 0.1232 |
| 1/5/2018 | Gaussian | No | 1090.22 | - | - | 0.00012 | 0.1200 | 0.0007 | 0.0485 | 0.0251 | 1.0100 | 0.0514 | 0.0010 |
| 1/6/2018 | Spherical | No | 1219.08 | - | - | 0.00000 | 0.0697 | 0.0020 | 0.0446 | 0.0150 | 1.0012 | 0.0539 | 0.0000 |
| 1/7/2018 | Gaussian | No | 1323.05 | - | - | 0.00023 | 0.2273 | 0.0085 | 0.0774 | 0.0062 | 1.0269 | 0.0932 | 0.0010 |
| 1/8/2018 | Gaussian | No | 1035.68 | - | - | 0.00000 | 0.0036 | 0.0010 | 0.0401 | 0.0164 | 1.0015 | 0.0406 | 0.0010 |
| 1/9/2018 | Spherical | No | 1043.13 | - | - | 0.00025 | 0.0021 | 0.0015 | 0.0416 | 0.0349 | 1.0043 | 0.0413 | 0.1086 |
| 1/10/2018 | Gaussian | No | 891.58 | - | - | 0.00004 | 0.0019 | 0.0003 | 0.0358 | 0.0119 | 1.0080 | 0.0354 | 0.0202 |
| 1/11/2018 | Spherical | No | 1348.62 | - | - | 0.00000 | 0.0011 | 0.0005 | 0.0245 | 0.0219 | 1.0007 | 0.0246 | 0.0000 |
| 1/12/2018 | Exponential | No | 1766.54 | - | - | 0.00000 | 0.0008 | 0.0003 | 0.0233 | 0.0109 | 0.9982 | 0.0235 | 0.0000 |
| 1/1/2019 | Exponential | No | 3291.74 | - | - | 0.00000 | 0.0010 | 0.0001 | 0.0201 | 0.0033 | 1.0003 | 0.0204 | 0.0000 |

**Table 2.** *Cont.*

| Date | Model | Anisotropy | Major Range (A0) | Minor Range (A0) | Direction (Degrees) | $C_0$ | C | Mean | RMSE | ME | RMSSE | ASE | RSD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/2/2019 | Spherical | No | 2243.60 | - | - | 0.00000 | 0.0012 | 0.0000 | 0.0193 | 0.0007 | 1.0015 | 0.0193 | 0.0000 |
| 1/3/2019 | Spherical | No | 2248.93 | - | - | 0.00000 | 0.0032 | 0.0008 | 0.0317 | 0.0239 | 0.9981 | 0.0328 | 0.0000 |
| 1/4/2019 | Gaussian | No | 1094.75 | - | - | 0.00001 | 0.0057 | 0.0002 | 0.0433 | 0.0043 | 1.0015 | 0.0471 | 0.0010 |
| 1/5/2019 | Exponential | No | 1633.17 | - | - | 0.00000 | 0.0068 | 0.0022 | 0.0689 | 0.0270 | 1.0034 | 0.0689 | 0.0000 |
| 1/6/2019 | Spherical | No | 1280.81 | - | - | 0.00000 | 0.0105 | 0.0010 | 0.0785 | 0.0077 | 1.0042 | 0.0789 | 0.0000 |
| 1/7/2019 | Spherical | No | 996.88 | - | - | 0.00000 | 0.0045 | 0.0001 | 0.0595 | 0.0040 | 1.0011 | 0.0596 | 0.0000 |
| 1/8/2019 | Gaussian | No | 2146.96 | - | - | 0.00080 | 0.0045 | 0.0001 | 0.0353 | 0.0012 | 1.0000 | 0.0358 | 0.1517 |
| 1/9/2019 | Spherical | No | 1340.11 | - | - | 0.00000 | 0.0014 | 0.0001 | 0.0283 | 0.0032 | 0.9934 | 0.0288 | 0.0000 |
| 1/10/2019 | Spherical | No | 983.21 | - | - | 0.00000 | 0.0005 | 0.0004 | 0.0209 | 0.0199 | 1.0164 | 0.0206 | 0.0000 |
| 1/11/2019 | Gaussian | No | 1280.59 | - | - | 0.00000 | 0.0023 | 0.0008 | 0.0249 | 0.0297 | 1.0003 | 0.0246 | 0.0010 |
| 1/12/2019 | Spherical | No | 1300.13 | - | - | 0.00000 | 0.0013 | 0.0013 | 0.0285 | 0.0183 | 0.9986 | 0.0277 | 0.0000 |
| 1/1/2020 | Spherical | No | 1087.35 | - | - | 0.00000 | 0.0006 | 0.0004 | 0.0208 | 0.0147 | 0.9995 | 0.0208 | 0.0000 |
| 1/2/2020 | Spherical | No | 891.58 | - | - | 0.00003 | 0.0001 | 0.0004 | 0.0114 | 0.0303 | 0.9973 | 0.0114 | 0.1685 |

Legend: A0 = range, $C_0$ = nugget effect, C = contribution, Direction (Degrees) = direction of anisotropic semivariogram models, ME = mean error, RMSE = root mean square error, ASE = average standard error, RMSSE = root mean square standardized error, and RSD = range of spatial dependence.

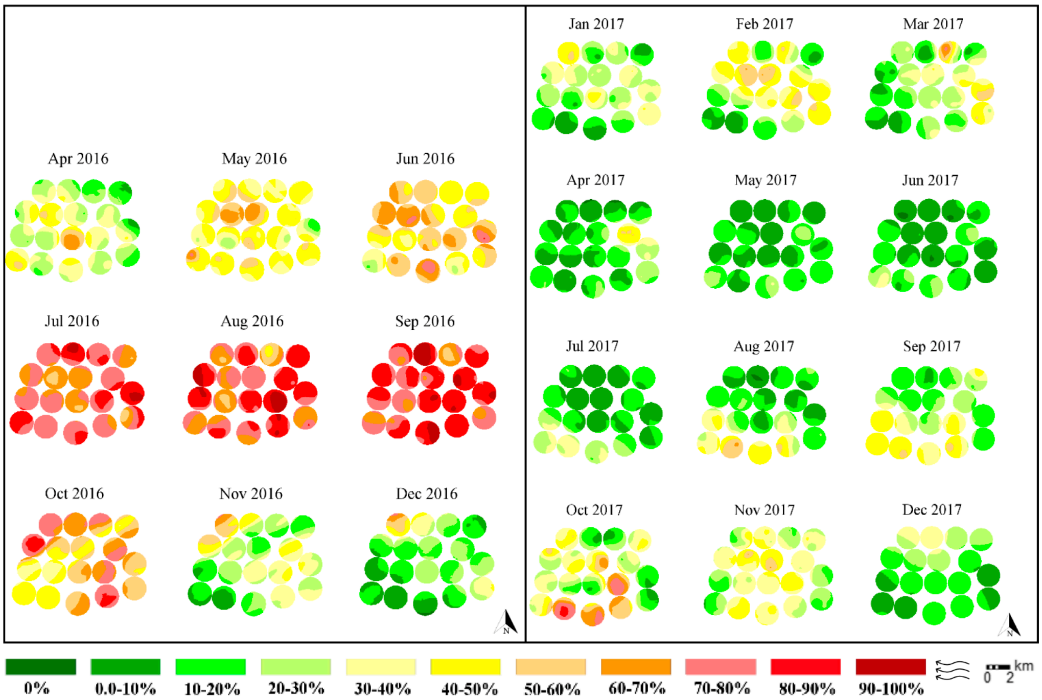


**Figure 3.** Spatial distribution maps of *Leucoptera coffeella* in the 18 coffee cultivation pivots of Milan Farm from April to December 2016 (year 1) and from January to December 2017 (year 2). Each circle on the map represents a 100 ha pivot. The color indicates the percentage (in the bars) of *L. coffeella* density.

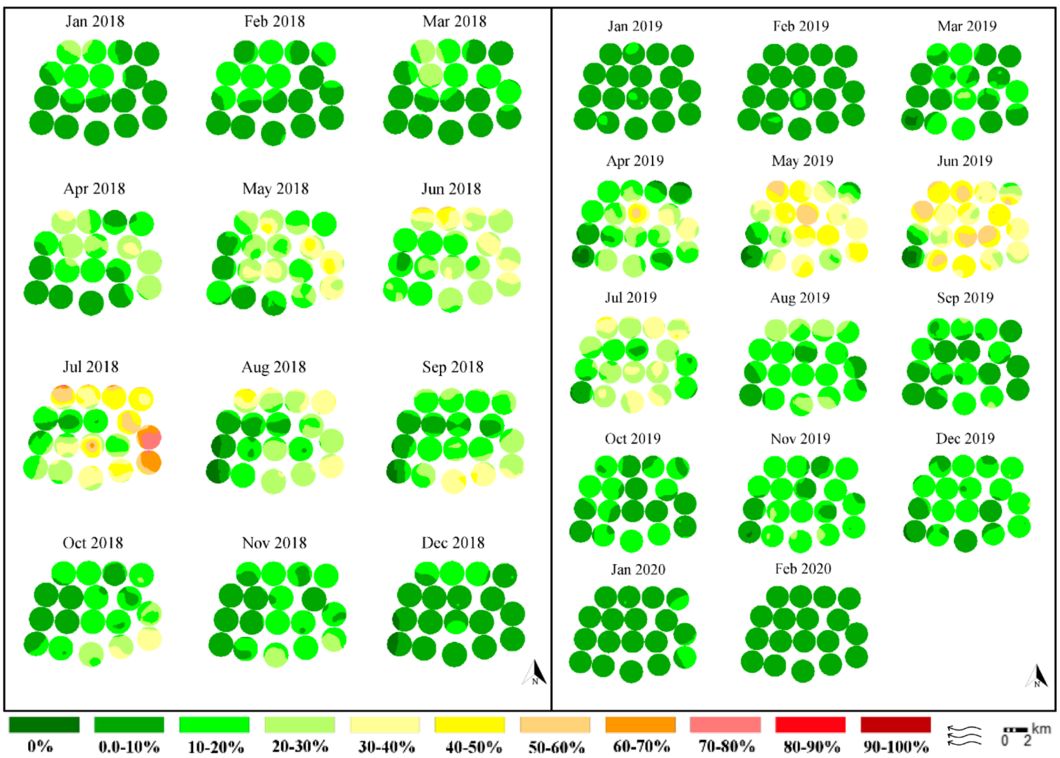


**Figure 4.** Spatial distribution maps of *Leucoptera coffeella* in the 18 coffee cultivation pivots of Milan Farm from January to December 2018 (year 3) and from January to December 2019 (year 4) and January and February 2020 (year 5). Each circle on the map represents a 100 ha pivot. The color indicates the percentage (in the bars) of *L. coffeella* density.

## 4. Discussion

The results presented in this study showed the spatial distribution of *L. coffeella* in coffee crops of the studied area. The interpolated maps of *L. coffeella* densities indicate the aggregation pattern. The term aggregation corresponds to a behavior in which the pest density is concentrated and not randomly distributed [33]. Dispersal of insect pests can be aggregated, uniform, or random (without a pattern). The spatial distribution of insects is considered aggregated when there is spatial data dependence between the sampled points [34] (Liebhold et al., 1993). The aggregation can be confirmed by the high sill values ($C_0$ + C), low nugget effect values ($C_0$), the adjustments made to the data in the semivariogram models, and the strong and moderate degree of spatial dependence.

The aggregation pattern of *L. coffeella* in the pivots may be associated with the nutritional status of the plants, the release of volatiles by the coffee plants, and pheromones by the adult pest [15,35]. Identifying aggregation areas allows control measures to be applied assertively in pest hotspots, reducing insecticides and pest dispersion in crops [36].

The spatial dependence of *L. coffeella* population densities in the present study was considered high (891.58 m to 4974.43 m). The range is the maximum distance beyond which no spatial correlation exists, and this parameter is most applicable to pest management [37]. Based on the range, it is possible to determine the spacing of pheromone bait [35] and the distance between the samples. These samples should be spaced according to the range because the points spaced below this cutoff value are spatially correlated (i.e., redundant) [38,39]. Therefore, this should avoid the miscalculation of population estimates [38].

The high range found in this study is due to the high flight capacity and dispersion of *L. coffeella* [35]. Thus, in the sampling plans of *L. coffeella* in coffee crops of the studied area, the distance between samples must be 891.58 m to 4974.43 m due to the spatial dependence of the *L. coffeella* population. The high value of the range is due to the distance between the sampled points. The range value can decrease or increase depending on the area size and distance between the samples. Studies should be conducted to verify if the pattern found in this study can be expanded to the entire Cerrado coffee region. In addition, studying distances between samples smaller than those used in this study can refine sampling.

In total, 91% of the omnidirectional models, that is, isotropic models, suggest that the dispersion of *L. coffeella* occurs in all directions. Furthermore, these models indicate that the dispersion of *L. coffeella* was not influenced by any physical barriers, wind direction, or altitudes. In addition, the flat relief of the Cerrado favors isotropy [36].

Pests usually initiate colonization along the edges of the crop [30,40]. This pattern was observed in some pivots in the first three years. Differently, in the fourth year, colonization started in the center of the crop.

The spatial distribution of pest insects in crops results from colonization and dispersal capacity [19,41]. Factors influencing the spatial distribution of these organisms in crops are the pest species characteristics, climatic elements, terrain relief, and surrounding vegetation [19,41,42].

Wind also plays a key role in dispersing insects over short and long distances [36,41,42]. The predominant wind direction in the region is from east to west. Thus, it was expected that the pest hotspot of *L. coffeella* infestation would move in the same direction from east to west, but this pattern was not observed in this study. This suggests that other factors unrelated to wind direction influenced the distribution of pests in the crop. Wind speed can affect the dispersion of *L. coffeella* by influencing the spread of sex pheromones in the crop [12,30,35]. In addition, the wind also carries olfactory odors from host plants, in the case of *L. coffeella* from coffee trees [41,43,44].

Surrounding vegetation can affect insect pest dispersion and colonization [45–48]. However, in this study, we did not observe the influence of the surrounding vegetation at all pivots on the distribution of *L. coffeella*. This may have occurred due to the low diversification of vegetation, composed mainly of pasture, small patches, permanent protection areas, native Cerrado vegetation, and other crops such as corn and soybeans.

We also observed an aggregation pattern in the distribution of *L. coffeella* within pivots. Furthermore, we observed pest hotspots with higher densities at some pivots over the years of this study. Hotspots are concentrations of the pest in only one location. The emergence of these hotspots may be related to the nutritional status of coffee plants, with the emission of sex pheromones, temperature increase, periods of low rainfall, insecticide efficiency, and the emergence of a population of *L. coffeella* resistant to the insecticides used [36,41,49–53]. The rapid dispersion of adults of *L. coffeella* gradually increases outbreaks and infestation in the entire crop area. Determining the beginning of the outbreaks and areas of emergence is essential for applying control methods, reducing insecticides, and reducing the environmental impact [36,41,54].

The attack of *L. coffeella* occurred throughout the year, but the highest densities were observed from July to November during the vegetative and flowering coffee plant phases. This time of year is characterized by high temperatures and low precipitation in the Brazilian Cerrado. As we have seen in this research, both the maximum air temperature and the rainfall directly affect the population of *L. coffeella* [55,56].

In conclusion, our study reports a high aggregation pattern and a high spatial dependence interval for *L. coffeella* in the studied area. Colonization starts at the edge of the crop. However, this pattern was not observed in the last year of evaluation. Furthermore, the surrounding vegetation did not influence the pest's dispersion in the field. From a pest management point of view, field sampling should be performed ranging from 891.58 m to 4974.43 m between each sample area, depending on the area size. Regarding isotropy, sampling should be performed equidistant as the pest is distributed equally in all directions. During periods of higher pest incidence, sampling should frequently be carried out at the pivot edges since most of the infestation starts from there. In the same way, control measures should be implemented in the field edges to reduce the population of *L. coffeella* before it outbreaks and the pest reaches the economic injury level.

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