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# Spatial and dynamic distribution of *Chrysoperla* spp. and *Leucoptera coffeella* populations in coffee *Coffea arabica* L

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**Abstract**
*Leucoptera coffeella* (Guérin-Mèneville, 1842) (Lepidoptera: Lyonetiidae) is one of the main pests of coffee. Controlling this insect requires effective management methods, prevention of insecticide resistance from overuse and an understanding of the pest's spatial distribution and natural enemies. Thus, our objectives were to (1) determine the spatial distribution of *Chrysoperla* spp. and *L. coffeella*; (2) evaluate the effects of biological control by analyzing the dynamics of *Chrysoperla* spp. and *L. coffeella* populations in the presence of predators; and (3) compare the quality of Arabica coffee beverages produced from areas employing chemical controls to those with biological controls. To this end, a commercial plot of *C. arabica* coffee (Catuaí 144) in Rio Paranaíba (MG, Brazil) was monitored. The population of *Chrysoperla* spp. and *L. coffeella* was evaluated every two weeks. The data were submitted to descriptive and geostatistical analysis. The population of *L. coffeella* remained low in February and March with the release of *Chrysoperla* spp. Moderate to strong spatial dependence was observed in the semivariograms, indicating that population aggregation occurred in both the pest and the predator. No change in the quality of the coffee beverages was observed between the biological control and pyrethroid insecticide treatments.

**Keywords** Coffee leaf miner · Biological control. Geostatistics. Predator · Geostatistics · Predator

## Introduction

*Leucoptera coffeella* (Guérin-Mèneville, 1842) (Lepidoptera: Lyonetiidae) is one of the main pests of coffee plantations (Pantoja-Gomez et al., 2019). The adults oviposit on leaves and the resulting caterpillars emerge and penetrate the leaves to feed on leaf mesophyll. This process produces galleries inside the leaves that increase ethylene production and lead to leaf senescence and defoliation. This in turn reduces coffee fruit yield and quality, plant longevity, and leads to productivity losses of up to 80% (Coffee-Tea.Co.UK, 2010; Pereira

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et al., 2007; Scalon et al., 2011). Coffee quality is determined officially and commercially by sensory analysis (cup proof), aspect, type, and sieve evaluations (Specialty Coffee Association of America – SCAA, 2014).

Coffee growers make heavy use of insecticides to control *L. coffeella* (Green et al., 2015). While pesticides increase harvest efficiency, they also accumulate in plant tissue and must be monitored (Barchańska & Plonka, 2018). Thus, more research is needed on methods of producing coffee with lower levels of insecticides.

Integrated Pest Management (IPM) provides an alternative to chemical control by increasing natural enemies that benefit natural biological control (Scalon et al., 2011). More resilient and sustainable approaches are urgently needed to minimize crop yield losses caused by pests and reduce the impacts of pest management on human health and the environment (Baker et al., 2020). Biological approaches such as biological control can provide viable alternatives.

Biological controls have been evaluated to determine the economic aspects and costs associated with the release, control efficiency and creation of natural enemies (Baker et al., 2020; Naranjo et al., 2015; Pan and Zhang, 2020). Several Brazilian and international companies are already producing and selling insects for insect-pest control (Lopes et al., 2019). These solutions can help reduce pesticide use, which can improve the quality of coffee beverages (Green et al., 2015). Arthropod predators belonging to the Chrysopidae family are highly voracious, insecticide-resistant predatory larvae (Ono et al., 2017) that have high reproductive potential, and can be used to control several agriculturally significant pests (Herrera et al., 2019).

However, field studies that could corroborate laboratory results for this predator are still scarce. In the present field study, we used geostatistical techniques (Calvo et al., 2018) to understand how pests and beneficial insects were distributed in the field, which can be useful for insect control strategies. Determining the spatial distribution of insects considers the geographical location of the samples and the spatial dependence between them (Martins et al., 2018). This information is helpful in Integrated Pest Management (IPM) and can support evolutionary insect-plant studies (Downes et al., 2017). IPM can benefit localized pest control by targeting optimal release locations (Martins et al., 2018; Pereira et al., 2018). In addition, spatial statistics can be used in ecological studies and to identify clusters. A cluster is an aggregate of an event, which could be a disease, concentration of minerals, or insect attacks within an area, and is the focus of research in spatial statistics (Cocu et al., 2005).

The objectives of this study were to (1) determine the spatial distribution of *Chrysoperla* spp. and *L. coffeella*; (2) evaluate the dynamics of *Chrysoperla* spp. and *L. coffeella* populations in areas of predator release to analyze the effect of biological control; and (3) determine the quality of Arabica coffee beverages from areas of chemical and biological controls.

## Materials and methods

### Experimental area

The experiment was conducted during the productive phase of a commercial coffee crop of *C. arabica*, cultivar Catuaí IAC-144, in autumn-winter 2019. This crop was 23 years old, spaced at 3.5×0.6 m in a simple row system over 2.6 ha, renewed through pruning in

2013 and located in the municipality of Rio Paranaiba, Minas Gerais, Alto Paranaiba, Brazil (19°10' 16" S and 46°12' 44" O, altitude – 1080 m). The predominant climate of the region is tropical dry type Aw according to the Köppen classification (Paranaiba River Basin Committee - Comitê da Bacia Hidrográfica de Rio Paranaíba, 2019).

## Obtaining *Chrysoperla* spp

The Chrysopids were obtained from mass breeding at the Associação Mineira de Produtores de Algodão (AMIPA) laboratory. The eggs were kept at 25 ºC, 60–70% relative humidity and photophase of 12:12 h until hatching. The larvae were separated into groups of 40–50 individuals per plastic pot (500 mL) and fed with 0.1 g of eggs of *Ephestia kuehniella* (Zeller) (Lepidoptera: Pyralidae). The resulting insects were released at the second instar stage when they were better prepared for competition in the field.

## Field release of *Chrysoperla* spp

To determine the optimal density of *C. externa* larvae needed to control *L. coffeella* in the field, the crop area was divided into four randomized blocks, with five treatments. The releases were performed every two weeks. The blocks were divided into 60×40 m (0.24 ha) plots that were approximately 100 m apart from each other. Each plot was divided into equidistant points (5 m) to allow for greater coverage and to reduce directional trends in sampling. Each plot consisted of 1200 coffee plants (240 plants per experimental unit). The five treatments were releases of 0, 500, 1000, 2000 and 5000 larvae/ha (Fig. 1). The coffee plants were in the reproductive phase (flowering), ranged from 1.6 to 1.8 m tall, spaced 0.5×4.0 m, and were cultivated under intensive light. The field conditions were characteristic of the Atlantic Forest region of coffee cultivation in Brazil, with temperatures ranging from 18 to 28 °C, relative humidity from 35 to 75%, 1200 mm precipitation per year and, an altitude of approximately 650 m above sea level.

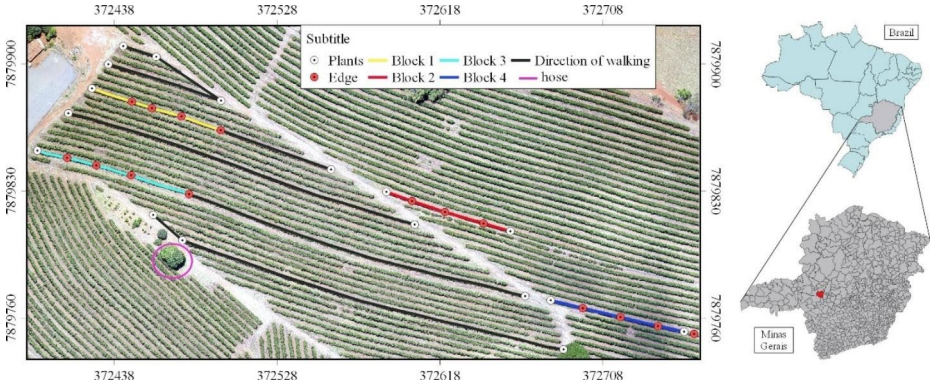


**Fig. 1** Aerial map of the blocks used in the population survey of *L. coffeella* and *Chrysoperla* spp

### Spatial distribution of *Chrysoperla* spp. and *L. coffeella*

The spatial distribution of *Chrysoperla* spp. and *L. coffeella* was determined by monitoring these insects on the plants at previously determined points (Fig. 1). Two hundred and forty plants were evaluated in each treatment (plot) every two weeks. The sampling unit for *L. coffeella* was collected from a leaf from the 3rd to the 5th pair of leaves on a branch located in the middle third of each coffee plant (Fig. 2). This location was chosen since coffee producers in Brazil generally sample the 4th pair of leaves for leaf analysis. Pupae were collected from the bottom third of the plant. *L. coffeella* was evaluated by directly counting the numbers of adults, eggs, pupae, mines, and larva. The adults were counted after vigorously shaking the plants. The infested leaf mines were examined with tweezers and scalpels. The eggs were counted on the leaf (adaxial position) using an Olympus stereomicroscope. For *Chrysoperla* spp., the number of adults and number of eggs per plant were determined by sampling two branches from each third of the plant canopy (apical, middle and basal). This was done since, at the time of the time of the experiment, no sampling unit had yet been defined in the literature for this family of predators.

### Sampling grid and population assessments of *Chrysoperla* spp. and *L. coffeella*

A regular sampling grid was defined with 101 geopositioned and equidistant sampling points, ranging from 5 to 23 m between points, evenly distributed throughout the study area. The same plant was evaluated each time and georeferenced in an x:y coordinate system. The area and the plants were georeferenced from control points obtained using GPS A3 FOIF, and aerial imaging from a drone (PHANTOM 4 ADVANCED model). The georeferenced plants were used to generate digitized maps to better visualize insect distribution. Geostatistics were used on the database by modeling experimental semivariograms for each analysis

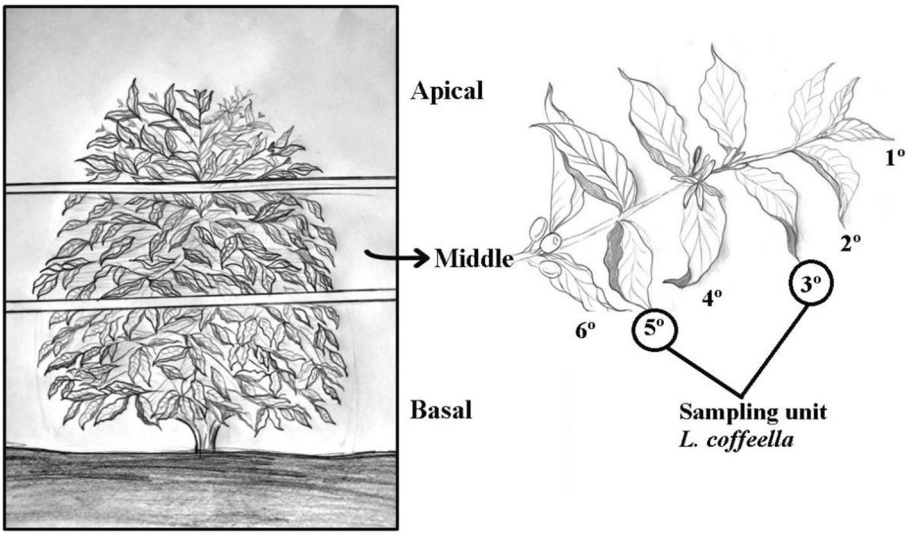


**Fig. 2** *L. coffeella* sampling unit from the 3rd to the 5th pair of leaves in the lateral branch of the middle third of the coffee plant

period and subsequent preparation of kriging maps. The insect populations collected at each sampling point were considered the regionalized variables Z, which varied continuously within the geographical space, from the longitude (X) and latitude (Y) of each sampling point.

Fitted models were used to estimate parameters called the nugget ($C_0$), baseline ($C_0+C$) and reach (a) effects. The semivariogram models were fit to linear, spherical, exponential and Gaussian models (Isaaks & Srivastava, 1989; Liebhold et al., 1993; Vieira et al., 1983) and according to the kriging method (Vieira et al., 1983). The degree of spatial dependence (GDE) was calculated from this model using the equation: $[(\mathrm{C}/\mathrm{C0}+C)]*100$. Spatial dependence was classified according to Cambardella et al., 1994, where the degree of spatial dependence is either strong (GDE ≤ 25.0%), moderate (25.0% < GDE ≤ 75.0%) or weak (GDE > 75.0%). The best fit model was selected when the coefficient of determination ($R^2$) was closest to one (Downing, 1986).

The descriptive and correlation statistics were analyzed using STATISTICA 8.0 software. Microsoft Excel 2016 was used to build the spatial distribution database, charts and tables. The semivariograms, mathematical models, and spatial distribution maps (kriging method) were generated and fitted using Surfer 11.0 (Golden Software) software.

The percentage of *L. coffeella* infestation was determined as:

$$\text{Infestation} = \frac{\text{number of leaves with active mines}}{\text{total number of leaves collected}} \text{x}100$$

## Investigating spatial autocorrelation using the Global and local bivariate Moran's I

The global Moran's I statistic determines if there is significant spatial autocorrelation in a variable compared to a spatially random distribution. A moving window is used where the z-scores of the kernel or central values is compared to neighboring values (wij = 1 or wij = 0). For this paper queen neighbors were used for all analysis and GeoDA 1.20 software was used. Spatial clusters of high or low values are identified are identified with positive values and negative spatial autocorrelation or spatial outliers are identified with negative values. The bivariate global Moran's I statistic quantifies the spatial dependence between two variables (Anselin et al., 2002). For the bivariate statistic the kernel value is for the first variable, but the neighboring values are for the second variable. Comparison of the first and second variables with each other is possible because both variables are standardized to z-scores. The bivariate statistic essentially determines if there is clustering or dispersion in the distribution of both variables and if there are negatively or positively correlated with each other. Univariate and bivariate Moran's I values range from −1 (perfect spatial dispersion) to +1 (perfect clustering). A bivariate Moran's I value of I = -1 indicates perfect clustering but a negative relationship between the two variables. A bivariate Moran's I = 0 indicates no correlation between variables and a random distribution while a bivariate Moran's I = 1 indicates perfect positive spatial dependence between variables namely perfect clustering of both variable and they are positively related to each other (Lu et al., 2010).

While univariate and bivariate global Moran's I values can help show the strength of spatial autocorrelation in data, and if there is a positive association between variables as well as clustering, the local Moran's I actually identifies the locations of clusters and spa-

tial outliers. We determined the spatial relationship among *Chrysoperla* spp. (predator) and *L. coffeella* (prey) using the local Moran index. The clusters were interpreted according to their significance ($p<0.05$) and the existence of spatial autocorrelation, such as: high-high (HH) = place with high frequency of predator and prey (positive correlation); low-high (LH) = location with low prey frequency and high predator frequency (negative correlation); low-low = place with low frequency of prey and predator; and not significant ($p>0.05$). To determine if local Moran's I values are significantly different from a spatially random distribution Monte Carlo simulation with 9,999 randomizations was applied to the Moran I values.

### Evaluation of coffee beverage quality in *Chrysoperla* spp. release blocks

The coffee fruit was harvested in June/2019 according to the random block design with six treatments (one with chemical control, and five with biological control) and 4 repetitions. Five liters of coffee were harvested from each plot. Soon after manual harvesting, the samples were dried in full sun and raked approximately 6–8 times a day until reaching 11 to 12% humidity. Subsequent processing was carried out at the Cooperativa Regional de Cafeicultores em Guaxupé LTDA (COOXUPÉ - Regional Cooperative of Coffee Growers in Guaxupé LTDA), where the fruit was peeled and stored in paper bags. The samples were then sent for sensory evaluation through the Cup Test by three specialized technicians, trained and qualified at GRANO TRADING located in Patos de Minas-MG, using the methodology of the Specialty Coffee Association of America – SCAA (2014). Several attributes were evaluated (fragrance/aroma of the grounds, flavor, finish, acidity, body, uniformity, balance, clean cup, sweetness) and a final total grade was assigned.

## Results

Larger *Chrysoperla* spp. populations were associated with smaller *L. coffeella* populations and *L. coffeella* populations decreased after *Chrysoperla* spp. release. Quantities of *L. coffeella* eggs and pupae remained low from February to July and the *L. coffeella* adult population increased when the number of *Chrysoperla* spp. eggs was lower (Fig. 3). *Chrysoperla* spp. egg counts increased until 30 days after the last release (April), after which numbers of both *Chrysoperla* spp eggs and adults dropped (Fig. 3).

All treatments within the release blocks of *Chrysoperla* spp. were above the control level for the Cerrado region (5%). However, in blocks with no releases, the percentage of leaves with active mines was 42.5%. This number dropped to 17.9% and 16.7% in the blocks with releases of 2000 and 5000 larvae $ha^{-1}$ (Fig. 4).

The spatial distribution of *Chrysoperla* spp. within the coffee crop was represented by spherical and Gaussian models, with a spatial dependence degree (GDE) that ranged from moderate ($25\% < GDE < 75\%$) to strong ($GDE < 25\%$) (Table 1). This indicates population aggregation of *Chrysoperla* spp., which can be seen on the map obtained from ordinary kriging (Fig. 5). The spatial distribution of *L. coffeella* was fit to the spherical semivariogram model with moderate to strong GDE, to the Gaussian model with moderate GDE and the exponential model with strong GDE. This also indicates population aggregation of *L.*

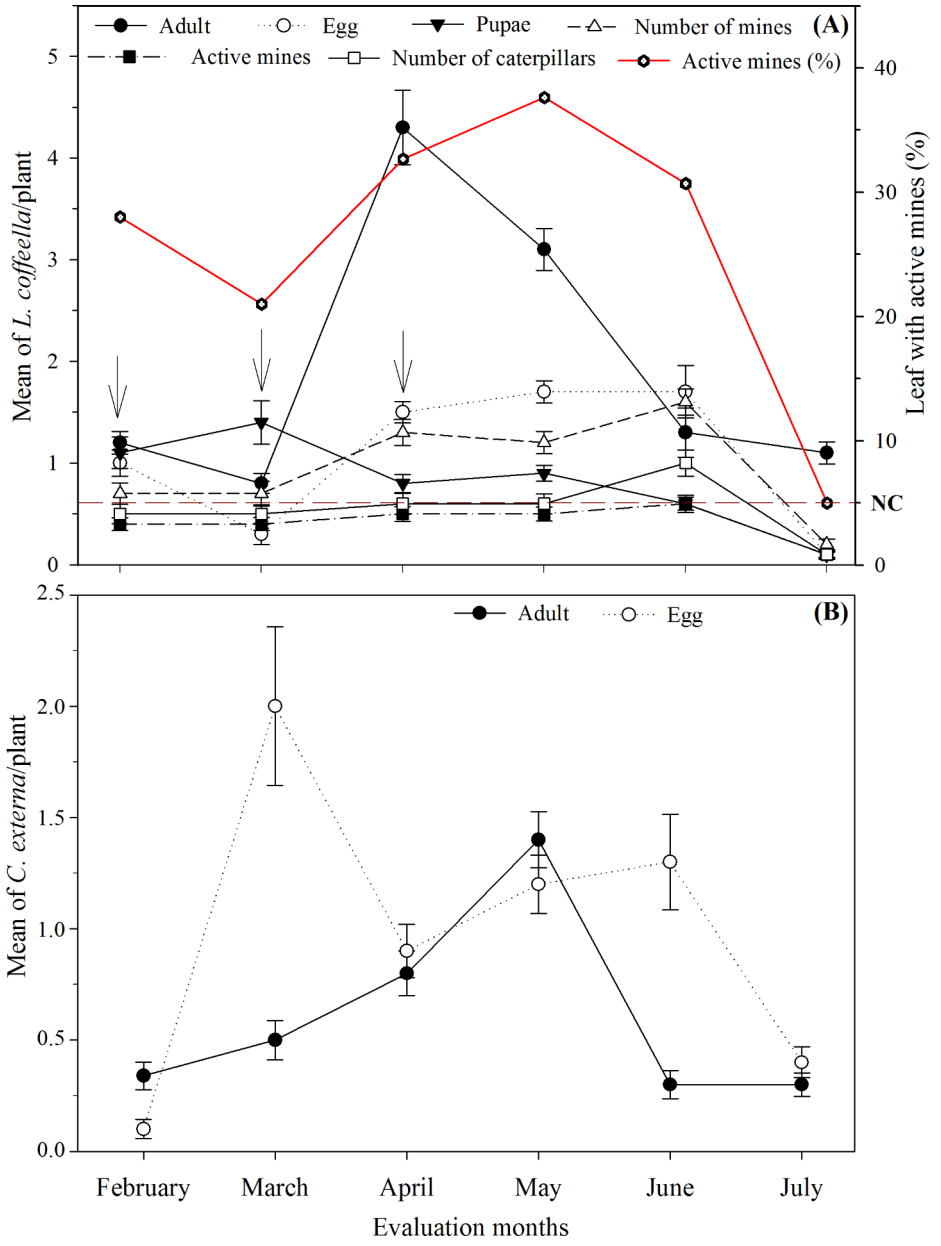


**Fig. 3** Mean ± standard error of the populations of *L. coffeella* **(A)** and *Chrysoperla* spp. **(B)** in C. *arabica*, Rio Paranaíba, MG, 2019. * NC = Cerrado control level. Arrows indicate when the *Chrysoperla* spp. larvae were released

*coffeella* that can be seen on the map (Fig. 6), as well as sites with varying degrees of predator and pest populations.

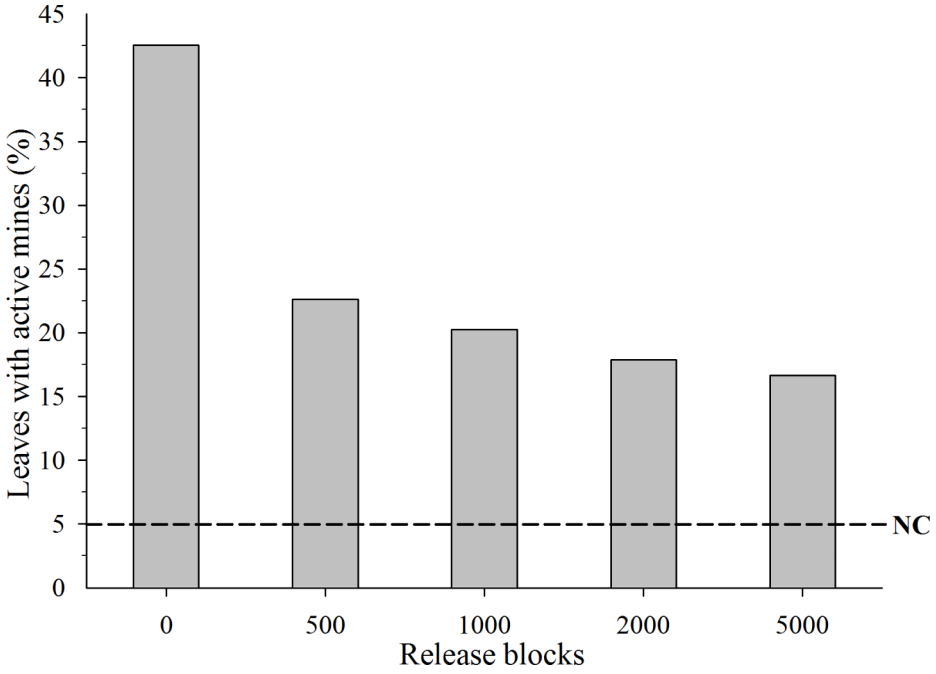


**Fig. 4** Percentage of leaves with active *L. coffeella* mines within *Chrysoperla* spp. release blocks, Alto Paranaíba, MG, 2019. ** NC = Cerrado control level

The reach (a) of spatial dependence for the number of *Chrysoperla* spp. adults ranged from 52 m before *Chrysoperla* spp. release to 92 m at 30 days after the release of *Chrysoperla* spp. in the field. The range (a) for the number of *L. coffeella* adults decreased from 63 m to 30 days after the release of *Chrysoperla* spp. to 20 m at 90 days after release. The number of eggs oscillated from 82 m to 30 days after release, to 16 m at 60 days after release, and then 57 m at 90 days after release of *Chrysoperla* spp. The pupa variable ranged from 10.5 m before the release of *Chrysoperla* spp. to 85 m at 60 days, and back to 13.4 m at 90 days after release of *Chrysoperla* spp. The active mine variable was 38 m before release, 25 m at 30 days after release, and 29 m at 90 days after release. Finally, regarding spatial error (nugget effect = $C_0$), 100% of the $C_0$ was close to 0 for the *Chrysoperla* population and more than 85% of the $C_0$ was less than 1 and close to 0 for the *L. coffeella* population.

Figure 5 shows the spatial distribution of the *Chrysoperla* spp. population. Here, the population was concentrated in one location with an average population density ranging from 0 to 4.4 adults per plant (Fig. 5). Figure 6 shows that the mean population density of *L. coffeella* ranged from 0 to 18 adults/plant, and 0 to 5 eggs, 0 to 7.9 pupa, 0 to 4 pupae, 0 to 2 active mines, and 0 to 4.2 live caterpillars per coffee leaf.

The spatial distribution maps for *Chrysoperla* spp. show that populations were very low before the release. After the releases (at 60 and 90 days) the number of *Chrysoperla* spp. adults increased in the vicinity of a mango tree (*Mangifera indica* L.) (Figs. 1 and 5). The spatial distribution maps for *L. coffeella* show that the largest foci (red area) of mines, active mines and caterpillars were before and at 30 days after the release of *Chrysoperla* spp., but

**Table 1** Semivariogram parameters fitted to the theoretical model parameter k to analyze the degree of spatial dependence (GDE) for the number of adults (NA) and eggs (NO) of *Chryposerla* spp., and the number of adults (NAD), eggs (NOV), pupae (NP), mines (NM), active mines (NMA) and caterpillars (NL) of *L. coffeella* in coffee plants. Rio Paranaíba. MG. 2019. [1]Nugget effect; [2]Spatial variance; [3]Reach (meters); [4]Calculated by the formula $C_0 / (C_0 + C_1)$; [5]Values were classified as: strong spatial dependence if $k < 25$, moderate spatial dependence if $25 \leq k \leq 75$ and weak spatial dependence if $k > 75$; - There was no fit

| Days after release (DAR) | Variable | Mean | Model | Parameters | | | [5] *K* | GDE |
|---|---|---|---|---|---|---|---|---|
| | | | | [1]$C_0$ | [2]$C_1$ | [3]a (m) | | |
| *Chrysoperla* spp. | | | | | | | | |
| 0 | NA | 0.34 | Spherical | 0.00 | 0.49 | 52.00 | 0.00 | Strong |
| | NO | 0.15 | | 0.11 | 0.09 | 85.00 | 0.60 | Moderate |
| 30 | NA | 0.53 | Spherical | 0.10 | 0.88 | 92.00 | 0.10 | Strong |
| | NO | 1.96 | - | - | - | - | - | - |
| 60 | NA | 0.78 | Gaussian | 0.63 | 0.49 | 54.00 | 0.60 | Moderate |
| | NO | 0.89 | - | - | - | - | - | - |
| 90 | NA | 1.37 | Gaussian | 0.48 | 1.85 | 65.00 | 0.20 | Strong |
| | NO | 1.23 | - | - | - | - | - | - |
| *L. coffeella* | | | | | | | | |
| 0 | NAD | 1.17 | Spherical | 0.00 | 1.62 | 36.00 | 0.00 | Strong |
| | NOV | 1.05 | Exponential | 0.00 | 1.53 | 22.00 | 0.00 | |
| | NP | 1.09 | | 0.00 | 2.25 | 10.50 | 0.00 | |
| | NM | 0.68 | Spherical | 0.30 | 0.86 | 35.00 | 0.26 | Moderate |
| | NMA | 0.36 | | 0.08 | 0.35 | 37.70 | 0.19 | Strong |
| | NL | 0.51 | | 0.30 | 0.64 | 33.00 | 0.32 | Moderate |
| 30 | NAD | 0.80 | Spherical | 0.17 | 1.14 | 63.00 | 0.13 | Strong |
| | NOV | 0.33 | | 0.36 | 0.88 | 82.00 | 0.29 | Moderate |
| | NP | 1.36 | | 1.60 | 3.30 | 44.00 | 0.33 | |
| | NM | 0.74 | | 0.40 | 1.00 | 38.00 | 0.29 | |
| | NMA | 0.37 | | 0.05 | 0.37 | 25.00 | 0.12 | Strong |
| | NL | 0.50 | | 0.21 | 0.63 | 32.00 | 0.25 | |

**Table 1** (continued)

| Days after release (DAR) | Variable | Mean | Model | Parameters | | | [5] $K$ | GDE |
|---|---|---|---|---|---|---|---|---|
| | | | | [1]$C_0$ | [2]$C_1$ | [3]a (m) | | |
| 60 | NAD | 4.34 | Spherical | 1.00 | 12.8 | 38.00 | 0.07 | Strong |
| | NOV | 1.49 | Exponential | 0.20 | 1.03 | 16.00 | 0.16 | |
| | NP | 0.80 | Spherical | 0.46 | 0.52 | 85.00 | 0.47 | Moderate |
| | NM | 1.35 | | | | | | |
| | NMA | 0.46 | - | - | - | - | - | - |
| | NL | 0.59 | | | | | | |
| 90 | NAD | 3.11 | Gaussian | 2.30 | 2.10 | 20.00 | 0.52 | Moderate |
| | NOV | 1.67 | Spherical | 0.25 | 1.22 | 57.00 | 0.17 | Strong |
| | NP | 0.92 | Exponential | 0.00 | 0.64 | 13.40 | 0.00 | |
| | NM | 1.21 | Spherical | 0.00 | 1.28 | 29.00 | 0.00 | |
| | NMA | 0.47 | | 0.20 | 0.27 | 30.00 | 0.43 | Moderate |
| | NL | 0.61 | Exponential | 0.10 | 0.87 | 15.00 | 0.10 | Strong |

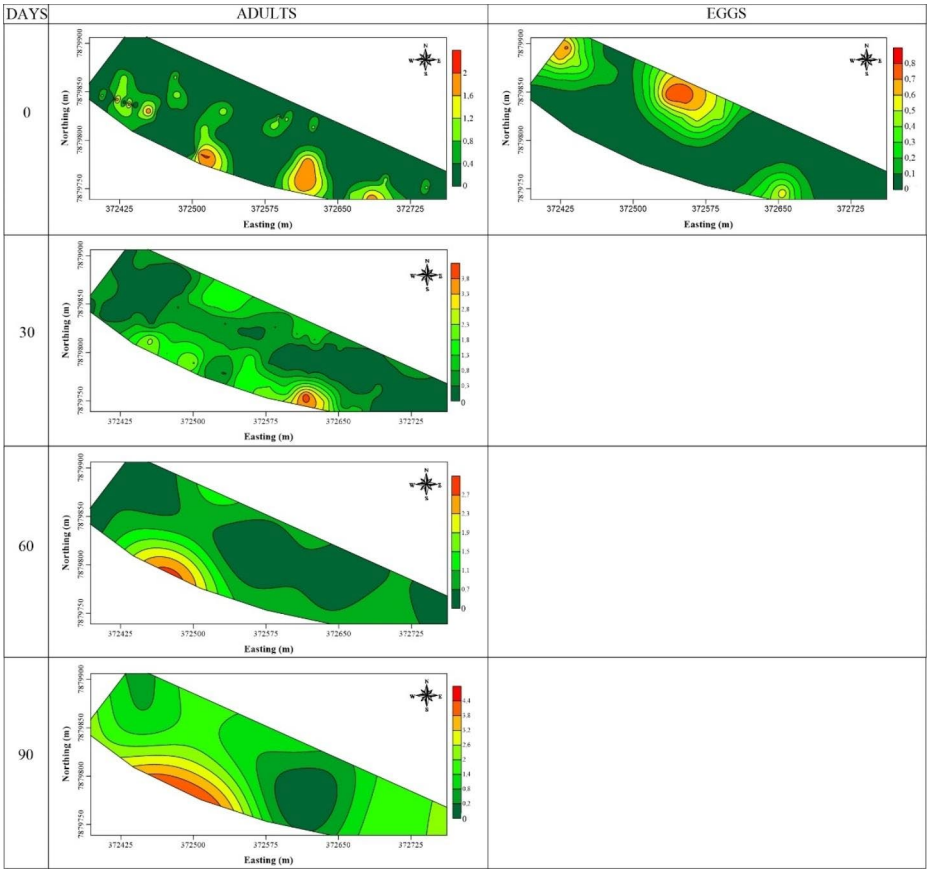


**Fig. 5** Spatial distribution map of *Chrysoperla* spp. at 0, 30, 60 and 90 days after release (DAR), produced by ordinary kriging. Rio Paranaíba, MG, 2019

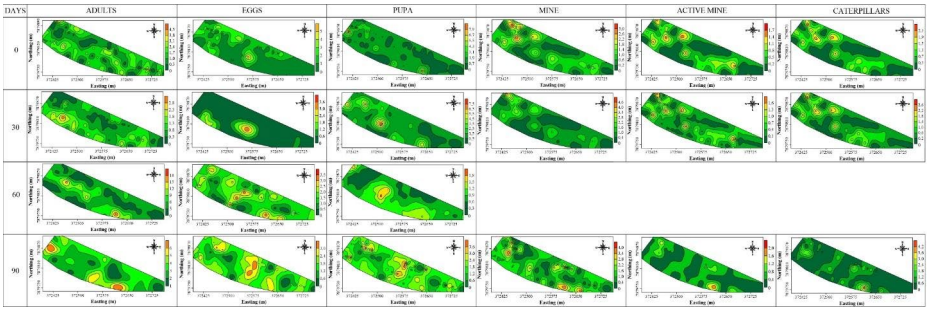


**Fig. 6** Spatial distribution map of *L. coffeella* at 0, 30, 60 and 90 days after release (DAR), produced by ordinary kriging. Rio Paranaíba, MG, 2019

less apparent at 90 days (Fig. 6), while the *L. coffeella* population was almost zero in areas with higher concentrations of *Chrysoperla* spp. (near *M. indica*) (Figs. 5 and 6).

Regarding spatial dependence, a significant (weak) spatial autocorrelation was detected between *L. coffeella* eggs x *Chrysoperla* spp. eggs (Moran I = 0.069, $p < 0.05$); *L. coffeella* eggs x *Chrysoperla* spp. adults (Moran I = -0.083, $p < 0.05$); *L. coffeella* pupa x *Chrysoperla* spp. eggs (Moran I = 0.18, $p < 0.05$) and *L. coffeella* adults x *Chrysoperla* spp. adults (Moran I = 0.068, $p < 0.05$). No spatial dependence ($p > 0.05$) was found at 0 days for the remaining combinations, indicating a random pattern (Table 2). Based on the bivariate Moran I index, spatial patterns between *Chrysoperla* spp. adults and all analyzed *L. coffeella* variables at 90 days after release were clustered ($p < 0.05$); however, the spatial dependence was weak at all life stages of *L. coffeella* with *Chrysoperla* spp. adults (Table 2). Therefore, the highest concentrations of *Chrysoperla* spp. adults were associated with reductions in the pest population of *L. coffeella* (Table 2; Fig. 5, and Fig. 6).

**Table 2** Spatial analysis of *L. coffeella* and *Chrysoperla* spp. at 0, 30, 60 and 90 days after release using the local bivariate Moran Index (Moran I). Rio Paranaiba, MG, Brazil, 2019

| Sampling | *Chrysoperla* spp. (egg) | | | *Chrysoperla* spp. (adult) | | |
|---|---|---|---|---|---|---|
| | Moran I | *P* value | Pattern | Moran I | *P* value | Pattern |
| *L. coffeella* (egg) | | | | | | |
| 0 days | 0.069 | 0.036 | Clustered | -0.083 | 0.008 | Clustered |
| 30 days | 0.032 | 0.200 | Random | 0.032 | 0.223 | Random |
| 60 days | -0.047 | 0.190 | Random | -0.027 | 0.230 | Random |
| 90 days | 0.049 | 0.127 | Random | -0.174 | 0.039 | Clustered |
| *L. coffeella (*pupa) | | | | | | |
| 0 days | 0.18 | 0.020 | Clustered | -0.028 | 0.203 | Random |
| 30 days | -0.030 | 0.265 | Random | 0.028 | 0.242 | Random |
| 60 days | -0.069 | 0.019 | Clustered | 0.048 | 0.043 | Clustered |
| 90 days | -0.027 | 0.257 | Random | -0.239 | 0.002 | Clustered |
| *L. coffeella* (mine) | | | | | | |
| 0 days | -0.001 | 0.458 | Random | -0.009 | 0.386 | Random |
| 30 days | -0.084 | 0.014 | Clustered | -0.076 | 0.045 | Clustered |
| 60 days | 0.089 | 0.036 | Clustered | 0.041 | 0.183 | Random |
| 90 days | -0.021 | 0.303 | Random | -0.229 | 0.005 | Clustered |
| *L. coffeella* (active mine) | | | | | | |
| 0 days | 0.043 | 0.128 | Random | 0.052 | 0.076 | Random |
| 30 days | -0.060 | 0.089 | Random | -0.038 | 0.218 | Random |
| 60 days | 0.049 | 0.174 | Random | -0.037 | 0.255 | Random |
| 90 days | -0.061 | 0.030 | Clustered | -0.175 | 0.004 | Clustered |
| *L. coffeella* (caterpillar) | | | | | | |
| 0 days | 0.045 | 0.109 | Random | 0.017 | 0.308 | Random |
| 30 days | -0.061 | 0.064 | Random | -0.079 | 0.041 | Clustered |
| 60 days | 0.034 | 0.224 | Random | -0.044 | 0.165 | Random |
| 90 days | -0.062 | 0.099 | Random | -0.198 | 0.001 | Clustered |
| *L. coffeella* (adult) | | | | | | |
| 0 days | -0.031 | 0.159 | Random | 0.068 | 0.027 | Clustered |
| 30 days | 0.141 | 0.007 | Clustered | 0.057 | 0.101 | Random |
| 60 days | -0.017 | 0.379 | Random | -0.016 | 0.372 | Random |
| 90 days | -0.049 | 0.174 | Random | -0.272 | 0.039 | Clustered |

**Table 3** Beverage evaluation at the release points.[1] Biological control area (BC) with different release numbers of *Chrysoperla* spp. caterpillars and areas treated with pyrethroid insecticide instead of BC.

| Treatments[1] | Beverage | Characteristics | Aspect |
|---|---|---|---|
| Block 1 | | | |
| 0 larvae | - | - | |
| 500 larvae | 83 | Raisins, dark chocolate | Fine Cup |
| 1000 larvae | - | - | |
| 2000 larvae | Hard good | - | Fine Cup |
| 5000 larvae | - | - | |
| Pyrethroid | 84.5 | Caramel | Fine Cup |
| Block 2 | | | |
| 0 larvae | - | - | |
| 500 larvae | - | - | |
| 1000 larvae | Hard good | - | Fine Cup |
| 2000 larvae | - | - | |
| 5000 larvae | - | - | |
| Pyrethroid | 84.5 | Caramel | Fine Cup |
| Block 3 | | | |
| 0 larvae | Hard good | - | Fine Cup |
| 500 larvae | - | - | |
| 1000 larvae | - | - | |
| 2000 larvae | Hard good | - | Fine Cup |
| 5000 larvae | Hard, 1 riada, 1 river | - | Good Cup |
| Pyrethroid | 84.5 | Caramel | Fine Cup |
| Block 4 | | | |
| 0 larvae | Hard, 1 riada | - | Good Cup |
| 500 larvae | 85.5 | Caramel, chocolate, rapadura | Fine Cup |
| 1000 larvae | Hard good | - | Fine Cup |
| 2000 larvae | 83 | Caramel, vanilla, chocolate | Fine Cup |
| 5000 larvae | 83 | Caramel | Fine Cup |
| Pyrethroid | 84.5 | Caramel | Fine Cup |

Our results show that local spatial autocorrelation exists between prey (*L. coffeella*) and predator (*Chrysoperla* spp.) population densities at specific locations in the coffee plantation (Fig. 7). Egg densities of *Chrysoperla* spp. were high and found at points with low prey densities (*L. coffeella*) (Fig. 7). At 90 days after release, prey and predator densities were low (Fig. 7H). In addition, spatial autocorrelation between prey and predator was always significant on the peripheries of the plantation area (Fig. 7).

*L. coffeella*Beverage quality did not differ significantly among treatments. The coffee presented a fine cup aspect with a score ranging from 84.50 to 85.75 for the insecticide and biological control treatments, respectively (Table 2).

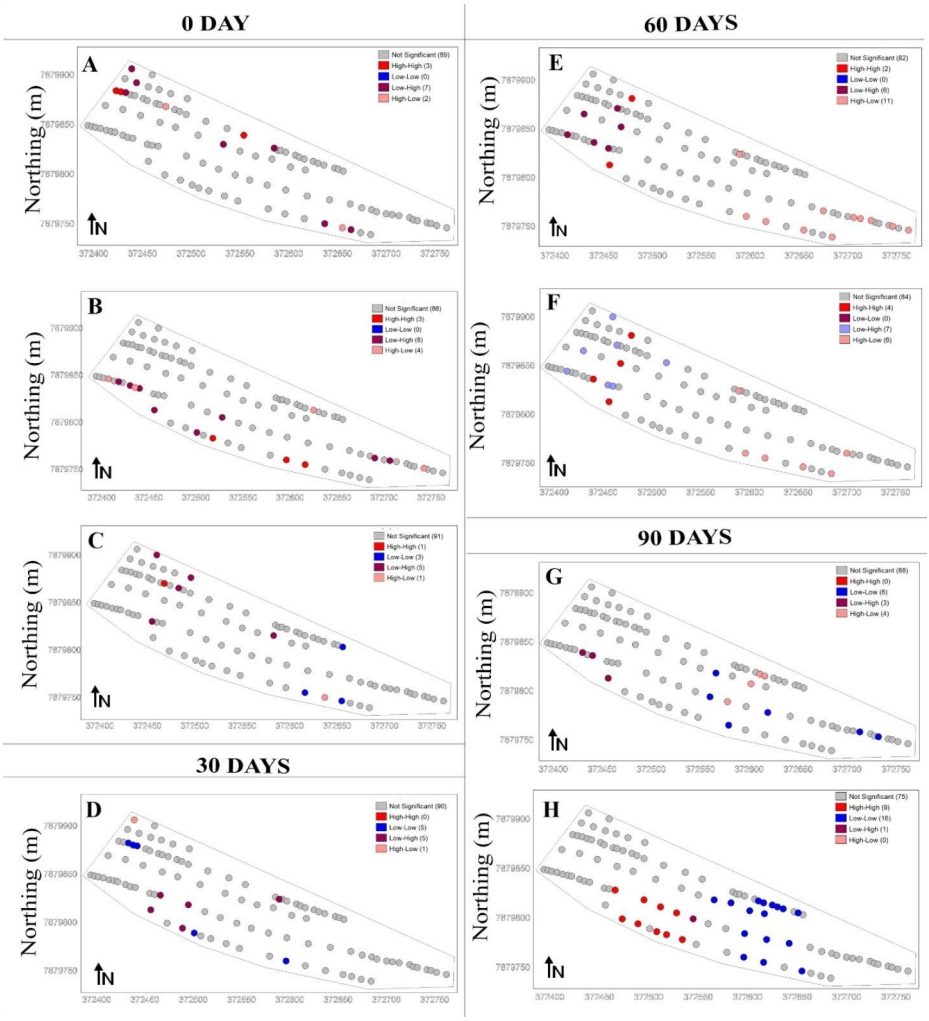


**Fig. 7** Maps showing bivariate LMI (local Moran's I) results for 0 days for LC (*L. coffeella*) egg and CE (*C. externa*) egg **(A)**, LC adult and CE adult **(B)**, LC pupa and CE egg **(C)**; 30 days for LC mine and CE egg **(D)**; 60 days for LC pupa and CE egg **(E)**; LC mine and CE egg **(F)**, and 90 days for LC mine and CE egg **(G)**, and for LC adult and CE adult **(H)**, in Rio Paranaíba, MG, 2019

## Discussion

The population of *L. coffeella* was highest from March to April when the population of *Chrysoperla* spp. was lowest. In treatments with 0 *Chrysoperla* spp./ha released, the number of active mines was 40% higher than the acceptable control level for the Cerrado (5%), while treatments with releases of 2000 and 5000 larvae/ha had active mine numbers 15% above the control level. In regions with milder climates, where this pest is not as severe, the control level is 30% of mined leaves with intact lesions. However, this control level does not apply to young coffee trees (<3 years), where defoliation, even at low levels, is harmful to

development (Gravena, 1983). Therefore, in these regions, except for younger coffee crops, treatments of 2000 to 5000 larvae/ha can efficiently maintain this pest population below the control level without other interventions.

The spatial distribution for *Chrysoperla* spp was fit to the spherical and Gaussian models while that of *L. coffeella* was fit to the spherical, Gaussian and exponential models. The fitted models showed a high degree of spatial dependence (moderate to strong), indicating an aggregated spatial distribution for both species. Thus, according to Liebhold et al. (1993), when spatial dependence exists between sampling points, the spatial distribution of insects is characterized as aggregate, and consequently, geostatistics provide the most appropriate tools for studying such populations. This agrees with Scalon et al. (2011) who classified the spatial distribution of *L. coffeella* as aggregate. The same authors also suggested that this aggregation of *L. coffeella* may be related to the low mobility of the insect.

An understanding of spatial aggregation is significant given its association with population dynamics and possible influence on monitoring and control measures (Blackshaw & Vernon, 2006; Corley et al., 2007). This behavior is influenced by several ecological factors such as habitat quality, field conditions, oviposition, natural enemies, and vegetation, which strongly affect insect distribution and abundance (Heisswolf et al., 2005).

Significant differences existed in the relationship between the various *Chrysoperla* spp. releases and *L. coffeella* populations. Specifically, subsequent releases reduced the reach of the adult variables, pupae, number of mines, active mines and caterpillars of *L. coffeella*, especially at 90 days after release of *Chrysoperla* spp. This parameter is an indicator of the maximum distance at which sampling points are correlated with each other, which in turn defines the limits of the spatial dependence of *L. coffeella* infestation and the maximum limits for sampling and monitoring intervals (Valeriano & Prado, 2001).

The spatial distributions of *Chrysoperla* spp. and *L. coffeella* could be correctly detected because the spacings between the sampling points (minimum 5 to 25 m) were lower than the ranges obtained for *Chrysoperla* spp. (52 to 92 m) and *L. coffeella* (10.5 and 85 m) and thus suitable for monitoring. While increasing the number of sampling points increases interpolation accuracy, it also increases the execution time and costs, which may be prohibitive for large sampling areas (Naranjo et at., 2015). Thus, optimal sampling can be achieved by extending the distance between sampling points to the maximum effective limit. In the current study, this distance was 25 m for optimal effective sampling *L. coffeella*, since more than 70% of the samples were above this distance.

According to Andriotti (2003), the lower the spatial error (nugget effect, $C_0$) in the semivariograms, the lower the error of the estimate. We found that 100% of the $C_0$ values for the *Chrysoperla* spp. population were close to 0 and more than 85% of the $C_0$ values of the *L. coffeella* population were less than 1 and close to 0, indicating low error levels in our estimates of predator and pest populations.

The distribution maps show that the highest concentrations of *Chrysoperla* spp. adults coincided with the lowest populations of *L. coffeella*, and that this higher concentration of *Chrysoperla* spp. occurred in the vicinity of a mango tree. According to Resende et al. (2014), extrafloral tree nectar attracts and increases populations of natural enemies. Ribeiro et al. (2013) showed that mango juice was the most effective lure in Chrysopidae traps. Rocha et al. (2015) studied the natural enemies of *Frankliniella* (Thysanoptera: Thripidae) in mango agroecosystems and found that species of the Chrysopidae family were most abundant during periods of mango inflorescence.

Lomeli-Floresa et al. (2009) observed that the population dynamics of *L. coffeella* were strongly affected by natural predators and parasitoids. Therefore, conserving biological controls can be an important source of mortality (Pereira et al., 2007). These results show that biological controls can significantly reduce pest populations.

Based on the bivariate Moran I analysis, the autocorrelation between *L. coffeella* eggs and *Chrysoperla* spp. eggs was grouped into 0 days, while all *L. coffeella* variables correlated negatively with *Chrysoperla* spp. adults at 90 days. Fernandes et al. (2008) observed that predatory wasp density correlated with the population density of *L. coffeella*. Samaranayake and Costamagna (2018) reported that levels of predator movement between soybeans and neighboring habitats were negatively associated with pest population size. These studies show that natural enemies can effectively reduce pest populations when they coincide spatially and temporally (Karimzadeh & Sciarretta, 2022).

The aggregated distribution among the different stages of *Chrysoperla* spp. and *L. coffeella* is due to the dependent relationship between predator and prey. *Chrysoperla* spp. has a high potential for *L. coffeella* predation and has consequently been uniformly released to control *L. coffeella* (Figueiredo et al., 2021). These same authors observed that areas with higher release densities of *Chrysoperla* spp. are associated with reductions in *L. coffeella* populations. These data corroborate the high-low (HL) clusters found in the present study, with high predator and low pest densities. Another important point is that *L. coffeella* is one of the preferred prey species for predators of the *Chrysoperla* genus (Dami et al., 2023). *L. coffeella* densities in coffee plantations vary over time because of the dispersion of these insects that change throughout the year (Alves et al., 2011; Scalon et al., 2011). The spatial variation of the predator, on the other hand, is probably related to prey quantities (Dami et al., 2023). Similar behavior has been observed between *L. coffeella* and other natural enemies in coffee plantations, such as predatory wasps (Fernandes et al., 2008) and parasitoids (Teodoro et al., 2009). Thus, *L. coffeella* clustering is influenced by local factors such as food availability and favorable environmental conditions, while their predators follow these pests in search of food, resulting in positive spatial relationships between the two species (Tscharntke et al., 2012; Clemente-Orta et al., 2020). Interestingly, *L. coffeella* and *Chrysoperla* spp. showed spatial autocorrelation at the outer limits of the coffee plantation. These areas are where adult insect flow is greatest and insect interaction is highest. Furthermore, traps containing insect attractants that are installed at the periphery capture more *L. coffeella* adults (Bacca et al., 2007).

We found that coffee beverage quality was similar in both the insecticide (pyrethroid) and biological control treatments. Coffee quality depends on the chemical composition of the fruit, which is determined by genetic factors, cultural traits and characteristics of the growing environment (Gumecindo-Alejo et al., 2021). Prete and Abraão (1996) define coffee quality as the sum of the physical attributes of raw fruit such as color, size, density, shape and uniformity, and attributes of roasted beans where characteristics expressed by taste and aroma stand out. According to these authors, beverage quality is the most important attribute in determining the marketability of coffee. For this reason, we examined beverage quality in the present study. Although there is not a significant difference in taste between the chemical pesticide applied and the pest predation method, the pest predation could be marketed as having no chemical pesticide applied and this could allow an increase in price as many consumers are willing to pay more for food that does not expose them to chemical pesticides.

## Conclusion

The spatial distribution of both pest and the predator (*L. coffeella* and *Chrysoperla* spp.) was considered aggregated. The aggregated distribution of *L. coffeella* could be used to define the location of sampling points and the number of samples needed in areas of greatest pest concentration. Moreover, these aggregated points could be used as optimal locations for carrying out other control methods, such as insecticides, possibly via drone. Drones could also be used to increase predator densities by releasing *Chrysoperla* spp eggs. where populations of *L. coffeella* are high and densities of *Chrysoperla* spp. are low. The release of *Chrysoperla* spp should be targeted at the periphery of the evaluated area, which showed the highest spatial autocorrelation. Thus, *Chrysoperla* spp. could be used in pest management since it is effective at maintaining *L. coffeella* populations below control levels. However, further studies are needed in the Cerrado region to determine the non-action level of *L. coffeella*. Thus, *Chrysoperla* spp. could be used in pest management since it is effective at maintaining *L. coffeella* populations below control levels. However, further studies are needed in the Cerrado region to determine the non-action level of *L. coffeella.* No change in coffee beverage quality was observed between insecticide and biological control treatments. Although there is not a relationship taste between the chemical pesticide applied and the pest predation method, the consumers probably will face some exposure to insecticide residues. Thus, are necessary finding alternatives to insecticides for the control of *L. coffeella*, such as the use of lacewings.

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## Declarations

**Ethics approval and consent to participate** The authors followed the Ethics guidelines of the Journal respecting the rights of third parties, such as copyright and/or moral rights.

**Consent for publication** All authors have agreed with the content and give explicit consent for submission.

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## References

Alves, M. C., Silva, F. M., Moraes, J. C., Pozza, E. A., Oliveira, S. O., Souza, J. C. S., & Alves, L. S. (2011). Geostatistical analysis of the spatial variation of the berry borer and leaf miner in a coffee agroecosystem. *Precision Agriculture*, *12*(1), 18–31. https://doi.org/10.1007/s11119-009-9151-z.

Andriotti, J. L. S. (2003). *Fundamentos de estatística e geoestatística (Fundamentals of Statistics and Geostatistics)* (p. 165). Ed. Unisinos.

Anselin, L., Syabri, I., & Smirnov, O. (2002). *Visualizing multivariate spatial correlation with dynamically linked windows*. University of California. CD-ROM. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.118.7163.

Bacca, T., Lima, E. R., Picanço, M. C., Guedes, R. N. C., & Viana, J. H. M. (2007). Sampling plan for the coffee leaf miner *Leucoptera coffeella* with sex pheromone traps. *Journal of Applied Entomology*, *132*(6), 430–438. https://doi.org/10.1111/j.1439-0418.2007.01264.x.

Baker, B. P., Greenb, T. A., & Lokerb, A. J. (2020). Biological control and integrated pest management in organic and conventional systems. *Biological Control*, *140*, 2–9. https://doi.org/10.1016/j.biocontrol.2019.104095.

Barchańska, H., & Plonka, J. (2018). Quality control of plant-based foods in terms of nutritional values: Influence of pesticides residue and endogenous compounds. *Food Control and Biosecurity Chap*, *12*, 407–449. https://doi.org/10.1016/B978-0-12-811445-2.00012-X.

Blackshaw, R. P., & Vernon, R. S. (2006). Spatiotemporal stability of two beetle populations in non-farmed habitats in an agricultural landscape. *Journal of Applied Ecology*, *43*(4), 680–689. https://doi.org/10.1111/j.1365-2664.2006.01167.x.

Calvo, M. V., Duarte, F., Borges, A., & Scatoni, I. (2018). Analysis of the spatial distribution of *Cydia pomonella* (L.) in Southern Uruguay using geostatistical tools. *Agrociencia Uruguay*, *22*(2), 1–11. https://doi.org/10.31285/agro.22.2.10.

Cambardella, C. A., Moorman, T. B., Novak, J. M., Parkin, T. B., Karlen, D. L., Turco, R. F., & Konopka, A. E. (1994). Field-scale variability of soil properties in Central Iowa soils. *Soil Science Society of America Journal*, *58*(1), 1501–1511. https://doi.org/10.2136/sssaj1994.03615995005800050033x.

Clemente-Orta, G., Madeira, F., Batuecas, I., Sossai, S., Juárez-Escario, A., & Albajes, R. (2020). Changes in landscape composition influence the abundance of insects on maize: The role of fruit orchards and alfalfa crops. *Agriculture Ecosystems & Environment*, *291*, 1–11. https://doi.org/10.1016/j.agee.2019.106805.

Cocu, N., Harrington, R., Hullé, M., & Rounsevell, M. D. A. (2005). Spatial autocorrelation as a tool for identifying the geographical patterns of aphid annual abundance. *Agricultural and Forest Entomology*, *7*(1), 31–43. https://doi.org/10.1111/j.1461-9555.2005.00245.x.

COFFEE-TEA.CO.UK (2010). *Coffee leafminer (Leucoptera coffeella)*. Retrieved October 30, 2019, from http://coffee-tea.co.uk/leafminer.php.

Comitê da Bacia Hidrográfica de Rio Paranaíba (CBH) (2019). *A Bacia/Clima (The Basin/Climate)*. Retrieved October 29, 2019, from http://cbhparanaiba.org.br/a-bacia/clima.

Corley, J. C., Villacide, J. M., & Bruzzone, O. A. (2007). Spatial dynamics of a Sirex noctilio woodwasp population within a pine plantation in Patagonia, Argentina. *Entomologia Experimentalis et Applicata*, *125*(3), 231–236. https://doi.org/10.1111/j.1570-7458.2007.00623.x.

Dami, B. G., Dos Santos, J. A., Barbosa, E. P., Rodriguez-Saona, C., & Vacari, A. M. (2023). Functional response of 3 green lacewing species (Neuroptera: Chrysopidae) to *Leucoptera coffeella* (Lepidoptera: Lyonetiidae). *Journal of Insect Science*, *23*(3), 1–8. https://doi.org/10.1093/jisesa/iead038.

Downes, S., Kriticos, D., Parry, H., Paull, C., Schellhorn, N., & Zalucki, M. P. (2017). A perspective on management of *Helicoverpa armigera*: Transgenic *bt* cotton, IPM, and landscapes. *Pest Management Science*, *73*(3), 485–492. https://doi.org/10.1002/ps.4461.

Downing, J. A. (1986). Spatial heterogeneity: Evolved behavior or mathematical artifact? *Nature*, *323*(6085), 255–257. https://doi.org/10.1038/323255a0.

Fernandes, F. L., Picanço, M. C., Zambolim, L., Queiroz, R. B., Pereira, R. M., Benevenute, J. da S., & Galdino, T. V. S. (2008). Spatial and temporal distributions of predator wasps and indirect irrigation effects. *Sociobiology*, 52(3), 543–551.

Figueiredo, G. P., Dami, B. G., Souza, J. M. R., Paula, W. B. S., Cabral, E. O., Rodriguez, S. C., & Vacari, A. M. (2021). Releases of *Chrysoperla externa* (Neuroptera: Chrysopidae) eggs for the control of the coffee leaf miner, *Leucoptera coffeella* (Lepidoptera: Lyonetiidae). *Arthropod Management Tests*, *46*(1), 1–2. https://doi.org/10.1093/amt/tsab148.

Gravena, S. (1983). Táticas de manejo integrado do bicho mineiro do cafeeiro *Perileucoptera cofeella* (Guérin- Mèneville, 1842): I. dinâmica populacional e inimigos naturais (Integrated management tactics of the coffee leaf miner *Perileucoptera cofeella* (Guérin-Mèneville, 1842): I. Population dynamics and natural enemies). *Anais da Sociedade Entomológica do Brasil*, *12*, 61–71.

Green, P. W. C., Davis, A. P., Cosse, A. A., & Vega, F. E. (2015). Can coffee chemical compounds and insecticidal plants be harnessed for control of major coffee pests? *Journal of Agricultural and food Chemistry*, *63*(43), 9427–9434. https://doi.org/10.1021/acs.jafc.5b03914.

Gumecindo-Alejo, A. L., Sánchez-Landero, L. A., Ortiz-Ceballos, G. C., Cerdán-Cabrera, C. R., Alvarado-Castillo, G. (2021) Factors related to coffee quality based on the "Cup of Excellence" contest in Mexico Coffee Science 161-10 10.25186/.v16i.1887

Heisswolf, A., Obermaier, E., & Poethke, H. J. (2005). Selection of large host plants for oviposition by a monophagous leaf beetle: Nutritional quality or enemy-free space. *Ecological Entomology*, *30*(3), 299–306. https://doi.org/10.1111/j.0307-6946.2005.00706.x.

Herrera, R. A., Campos, M., González-Salvadó, M., & Ruano, F. (2019). Abundance and population decline factors of Chrysopidae juveniles in olive groves and adjacent trees. *Insects*, *10*(5), 1–18. https://doi.org/10.3390/insects10050134.

Isaaks, E. H., & Srivastava, R. M. (1989). *An introduction to applied geostatistics* (p. 561). Oxford University Press.

Karimzadeh, R., & Sciarretta, A. (2022). Spatial patchiness and association of pests and natural enemies in agro-ecosystems and their application in precision pest management: A review. *Precision Agriculture*, *23*, 1836–1855. https://doi.org/10.1007/s11119-022-09902-6.

Liebhold, A. M., Rossi, R. E., & Kemp, W. P. (1993). Geostatistic and geographic information system in applied insect ecology. *Annual Review of Entomology*, *38*(1), 303–327. https://doi.org/10.1146/annurev.en.38.010193.001511.

Lopes, M. C., Ribeiro, A. V., Costa, T. L., Arcanjo, L. P., Farias, E. S., Santos, A. A., & Picanço, M. C. (2019). Practical sampling plan for *Liriomyza huidobrensis* (Diptera: Agromyzidae) in tomato crops. *Journal of Economic Entomology*, *112*(4), 1946–1952. https://doi.org/10.1093/jee/toz091.

Lu, X., Robertson, A. E., Byamukama, E., & Nutter, F. W. (2010). Prevalence, incidence, and spatial dependence of soybean mosaic virus in iowa. *Phytopathology*, *100*(9), 931–940. https://doi.org/10.1094/PHYTO-100-9-0931.

Martins, J. C., Picanço, M. C., Gonring, A. H., Galdino, T. V., & Guedes, R. N. (2018). Assessing the spatial distribution of *Tuta absoluta* (Lepidoptera: Gelechiidae) eggs in open-field tomato cultivation through geostatistical analysis. *Pest Management Science*, *74*(1), 30–36. https://doi.org/10.1002/ps.4664.

Naranjo, S. E., Ellsworth, P. C., & Frisvold, G. B. (2015). Economic value of biological control in integrated pest management of managed plant systems. *Annual Review of Entomology*, *60*, 621–645. https://doi.org/10.1146/annurev-ento-010814-021005.

Ono, É. K., Zanardi, O. Z., Santos, K. F. A., & Yamamoto, P. T. (2017). Susceptibility of *Ceraeochrysa cubana* larvae and adults to six insect growth-regulator insecticides. *Chemosphere*, *168*, 49–57. https://doi.org/10.1016/j.chemosphere.2016.10.061.

Pan, Y. X., & Zhang, F. (2020). Advances in biological control of the german cockroach, *Blattella germanica* (L). *Biological Control*, *142*, 1–12. https://doi.org/10.1016/j.biocontrol.2019.104104.

Pantoja-Gomez, L. M., Correa, A. S., Oliveira, L. O., & Guedes, R. N. C. (2019). Common origin of brazilian and colombian populations of the neotropical coffee leaf miner, *Leucoptera coffeella* (Lepidoptera: Lyonetiidae). *Journal of Economic Entomology*, *112*(2), 924–931. https://doi.org/10.1093/jee/toy416.

Pereira, E. J. G., Picanço, M. C., Bacci, L., Crespo, A. L. B., & Guedes, R. N. C. (2007). Seasonal mortality factors of the coffee leafminer, *Leucoptera coffeella*. *Bulletin of Entomological Research*, *97*(4), 421–432. https://doi.org/10.1017/S0007485307005202.

Pereira, R. M., Galdino, T. V. S., Rodrigues-Silva, N., Silva, R. S., Souza, T. C., & Picanço, M. C. (2018). Spatial distribution of beetle attack and its association with mango sudden decline: An investigation using geostatistical tools. *Pest Management Science*, *75*(5), 1346–1353. https://doi.org/10.1002/ps.5251.

Resende, M. Q., Venzon, M., Perez, A. L., Cardoso, I. M., & Janssen, A. (2014). Extrafloral nectaries of associated trees can enhance naturalpest control. *Agriculture Ecosystems & Environment*, *188*, 198–203. https://doi.org/10.1016/j.agee.2014.02.024.

Ribeiro, A. E. L., Castellani, M. A., Moreira, A. A., Pérez-Maluf, R., Silva, E., C. G. V., & Santos, A. S. (2013). Diversidade e sazonalidade de crisopídeos (Neuroptera: Chrysopidae) em plantas de urucum (diversity and seasonality of lacewings (Neuroptera: Chrysopidae) in annatto plants). *Horticultura Brasileira*, *31*(4), 636–641. https://doi.org/10.1590/S0102-05362013000400021.

Rocha, F. H., Infante, F., Castillo, A., Ibarra-Nuñez, G., Goldarazena, A., & Funderburk, J. E. (2015). Natural enemies of the *Frankliniella* complex species (Thysanoptera: Thripidae) in ataulfo mango agroecosystems. *Journal of Insect Science*, *15*(1), 1–5. https://doi.org/10.1093/jisesa/iev096.

Samaranayake, K. G. L. I., & Costamagna, A. C. (2018). Levels of predator movement between crop and neighboring habitats explain pest suppression in soybean across a gradient of agricultural landscape complexity. *Agriculture Ecosystems & Environment*, *259*, 135–146. https://doi.org/10.1016/j.agee.2018.03.009.

SCAA 2014. SCAA Protocol Cupping Specialty Coffee, *https://www.scaa.org/?page=resources&d=cupping-protocols*, https://www.scaa.org/?page=resources&d=cupping-protocols (2023).

Scalon, J. D., Avelar, M. B. L., de Alves, G. F., & Zacarias, M. S. (2011). Spatial and temporal dynamics of coffee-leaf-miner and predatory wasps in organic coffee field in formation. *Ciência Rural*, *41*, 646–652. https://doi.org/10.1590/S0103-84782011005000037.

Teodoro, A. V., Tscharntke, T., & Klein, A. M. (2009). From the laboratory to the field: Contrasting effects of multi-trophic interactions and agroforestry management on coffee pest densities. *Entomologia Experimentalis et Applicatta*, *131*(2), 121–129. https://doi.org/10.1111/j.1570-7458.2009.00840.x. https://doi-org.ez35.periodicos.capes.gov.br/.

Tscharntke, T., Tylianakis, J. M., Rand, T. A., Didham, R. K., Fahrig, L., Batáry, P., Bengtsson, J., Clough, Y., Crist, T. O., Dormann, C. F., Ewers, R. M., Fründ, J., Holt, R. D., Holzschuh, A., Klein, A. M., Kleijn, D., Kremen, C., Landis, D. A., Laurance, W., Lindenmayer, D., Scherber, C., Sodhi, N., Steffan-Dewenter, I., Thies, C., Putten, W. H., & Westphal, C. (2012). Landscape moderation of biodiversity patterns and processes-eight hypotheses. *Biological Reviews of the Cambridge Philosophical Society*, *87*(3), 661–685. https://doi.org/10.1111/j.1469-185X.2011.00216.x.

Valeriano, M. M., & Prado, H. (2001). Técnicas de geoprocessamento e de amostragem para o mapeamento de atributos anisotrópicos do solo (geoprocessing and sampling techniques for mapping anisotropic soil attributes). *Revista Brasileira de Ciência do Solo*, *25*, 997–1005. https://doi.org/10.1590/S0100-06832001000400022.

Vieira, S. R., Hatfield, J. L., Nielsen, D. R., & Biggar, J. W. (1983). Geostatistical theory and application to variability of some agronomical properties. *Hilgardia*, *51*(3), 1–75. https://doi.org/10.3733/hilg.v51n03p075.



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