ADRIANA HELENA WALERIUS

SEASONAL VARIATION, SPATIAL DISTRIBUTION AND DECISION–MAKING SYSTEM TO CONTROL *Leucoptera coffeella* IN COFFEE ARABICA FIELDS

Thesis submitted to the Entomology Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

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VIÇOSA - MINAS GERAIS
2022

Ficha catalográfica elaborada pela Biblioteca Central da Universidade Federal de Viçosa - Campus Viçosa

T

Walerius, Adriana Helena, 1989-

W171s
2022

Seasonal variation, spatial distribution and decision–making system to control *Leucoptera coffeella* in coffee arabica fields / Adriana Helena Walerius. – Viçosa, MG, 2022.

1 tese eletrônica (84 f.): il. (algumas color.).

Texto em inglês.

Orientador: Ângelo Pallini Filho.

Tese (doutorado) - Universidade Federal de Viçosa, Departamento de Entomologia, 2022.

Inclui bibliografia.

DOI: https://doi.org/10.47328/ufvbbt.2022.385

Modo de acesso: World Wide Web.

1. Bicho-mineiro-do-café - Controle. 2. Café - Doenças e pragas. 3. Geologia - Métodos estatísticos. 4. Agricultura de precisão. 5. Bicho-mineiro-do-café - Fatores climáticos. I. Filho, Ângelo Pallini, 1965-. II. Universidade Federal de Viçosa. Departamento de Entomologia. Programa de Pós-Graduação em Entomologia. III. Título.

CDD 22. ed. 595.78

Bibliotecário(a) responsável: Bruna Silva CRB6/2552

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APPROVED: March 28, 2022.

Assent:

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ACKNOWLEDGEMENTS

To the Federal University of Viçosa for the opportunity to complete the postgraduate course.

To the Prof. Dr. Angelo Pallini for having me as a doctoral student in his laboratory. Thank you for your orientation, support, trust, and teachings.

To the Prof. Dr. Marcelo Coutinho Picanço for the opportunity to have him as a co-adviser. Thank you for having me in your laboratory and for all the teachings, trust, friendship, understanding, and patience.

To the examining board members, Ricardo Siqueira da Silva, Tamiris Alves de Araújo, Elem Fialho Martins, Marcelo Coutinho Picanço, for their availability and for all their ideas and reflections.

To the members of the Postgraduate Program in Entomology, especially the program professors. His teachings contributed positively to my formation.

To the secretary of the Postgraduate Program in Entomology, Eliane, for the prompt service whenever requested.

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

To the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), for financial support.

To Olam Coffee Company for granting the scholarship.

To the employees of Olam Coffee Company for their support and availability.

To my colleagues in the Acarology laboratory, especially Italo, Vanessa, and Paola, who has always been with me laboratory inside and outside.

To my colleagues from the Integrated Pest Management laboratory, who welcomed me with open arms and helped me in everything I needed. Special thanks to the interns Renata, Emilio, Júlia, and Jherssyka, who were by my side during the experiments.

To everyone who somehow contributed to the realization of my doctorate.

Finally, I thank my family to my father, Ademir Luis Walerius, and my mother, Lurdes Maria Walerius. You never measured efforts to make my dreams come true. To my sister Andresa Walerius, for all the support, love, and friendship; you are always with me no matter the distance.

To my lovely friend, boyfriend, fiance, and husband, Paulo Antonio Santana Jr., your love and support were essential to finishing this step of my life.

To God, “I can do all things through him who strengthens me.”

ABSTRACT

WALERIUS, Adriana Helena, D.Sc., Universidade Federal de Viçosa, March 2022. **Seasonal variation, spatial distribution and decision–making system to control of the *Leucoptera coffeella* in coffee arabica fields.** Adviser: Angelo Pallini. Co-advisers: Marcelo Coutinho Picanço and Madelaine Venzon.

Coffee is the world's second-largest commodity and represented a global market of US$ 102.02 billion dollars in 2020. The Neotropical region is the main coffee producer globally, accounting for more than 56% of the world's production of *Arabica coffee*. In this region, the coffee leaf miner *Leucoptera coffeella* is one of key coffee pests. This pest can decrease productivity by around 50 to 87% at high densities. Several factors can influence the *L. coffeella* population dynamics in the field. Therefore, prior knowledge of the areas and seasons of higher incidence of *L. coffeella* is essential to field management. The objective of this study was to evaluate the seasonality of the *L. coffeella* population and the factors that regulate its dynamics in coffee crops located in the Atlantic Forest and the Cerrado biomes. We aim to determine the spatial distribution of *Leucoptera coffeella* in coffee crops in the Cerrado through geostatistical analyses and propose a decision-making control system based on management zones. *L. coffeella* densities were higher in the Cerrado area compared to the Atlantic Forest. In the Cerrado, air temperature and potential evapotranspiration were higher, while rainfall was lower. These data are correlated with the high densities of *L. coffeella* in the fields. The highest population densities were observed between July and October, when the coffee plants were in the fruiting and flowering phases. The minimum, optimum and maximum temperatures for the development of the pest were 16.59, 26.81, and 34.8°C, respectively. Therefore, the climatic elements in each biome influenced the spatio-temporal dynamics of *L. coffeella*. Geostatistical analysis showed an aggregated distribution of *L. coffeella* in the Cerrado field. Colonization generally started at the edges of the crop, except in the last year of evaluation. Pest outbreaks appeared at different pivots and different locations within the pivots. Due to isotropy, sampling must be done equidistantly, as the pest is evenly distributed in all directions. The programs that use sampling and level of control (30% of active mined leaves) in decision making were the most efficient and assertive in controlling *L. coffeella*. Management zones reduce insecticide use by 70% compared to conventional control over the whole area. The information provided in this study is essential for designing and implementing efficient control strategies, thus reducing production costs and the harmful effects of pesticide use.

Keywords: *Coffea arabica*. Coffe Leaf miner. Population Fluctuation. Climatic Elements. Geostatistics. Integrated Pest Management. Precision Agriculture.

RESUMO

WALERIUS, Adriana Helena, D.Sc., Universidade Federal de Viçosa, março de 2022. **Variação espacial, distribuição e sistemas de tomada de decisão para o controle de *Leucoptera coffeella* em cultivos de café arábica.** Orientador: Angelo Pallini. Coorientadores: Marcelo Coutinho Picanço e Madelaine Venzon.

O café é a segunda maior commodity do mundo e representou um mercado global de US$ 102,02 bilhões de dólares em 2020. A região Neotropical é a principal produtora de café no mundo, responsável por mais de 56% da produção mundial de café arábica. Nesta região, o bicho-mineiro *Leucoptera coffeella* é uma das principais pragas do café. Esta praga pode diminuir a produtividade em torno de 50 a 87% em altas densidades. Vários fatores podem influenciar a dinâmica populacional de *L. coffeella* em campo. Portanto, o conhecimento prévio das áreas e épocas de maior incidência de *L. coffeella* é essencial para o seu manejo no campo. O objetivo deste estudo foi avaliar a sazonalidade da população de *L. coffeella* e os fatores que regulam a dinâmica populacional em cultivos de café localizados nos biomas de Mata Atlântica e Cerrado. O segundo objetivo foi determinar a distribuição espacial de *L. coffeella* em cafezais do Cerrado por meio de análises geoestatísticas e propor um sistema de tomada de decisão de controle baseado em zonas de manejo. As densidades de *L. coffeella* foram maiores na área do Cerrado em comparação com a Mata Atlântica. No Cerrado, a temperatura do ar e a evapotranspiração potencial foram maiores, enquanto a precipitação pluviométrica foi menor. Esses dados estão correlacionados com as altas densidades de *L. coffeella* nos campos. As maiores densidades populacionais foram observadas entre julho e outubro, quando os cafeeiros estavam nas fases de frutificação e floração. As temperaturas mínima, ótima e máxima para o desenvolvimento da praga foram 16,59, 26,81 e 34,8°C, respectivamente. Portanto, os elementos climáticos em cada bioma influenciaram a dinâmica espaço-temporal de *L. coffeella*. A análise geoestatística mostrou uma distribuição agregada de *L. coffeella* no campo de Cerrado. A colonização iniciou-se geralmente nas bordas da lavoura, exceto no último ano de avaliação. Os surtos da praga apareceram em diferentes pivôs e diferentes locais dentro dos pivôs. Devido à isotropia, a amostragem deve ser feita de forma equidistante, pois a praga está distribuída uniformemente em todas as direções. Os programas que utilizam amostragem e nível de controle (30% de folhas ativas minadas) na tomada de decisão foram os mais eficientes e assertivos no controle de *L. coffeella*. As zonas de manejo reduzem o uso de inseticidas em 70% em comparação com o controle convencional em toda a área. As informações fornecidas neste estudo são essenciais para o delinear e implementar estratégias de controle eficientes, reduzindo assim os custos de produção e os efeitos nocivos do uso de agrotóxicos.

Palavras-chave: *Coffea arabica*. Bicho mineiro do café. Flutuação Populacional. Elementos Climáticos. Geoestatística. Manejo Integrado de Pragas. Agricultura de Precisão.

SUMÁRIO

GENERAL INTRODUCTION

Coffee is the world's second-largest commodity and holds a significant share of global agribusiness (Alves and Lindner, 2020; Avelino et al., 2018; Lomelí-Flores et al., 2010; Vegro and Almeida, 2020). Its production is of great economic importance in the countries where it is grown and represented a global market of US 102.02 billion dollars in 2020 (Intelligence, 2021). Besides its economic importance, coffee production has an essential social role in the countries, promoting livelihoods for approximately 125 million people (Avelino et al., 2018).

The Neotropical region, formed by Central and South American countries, is the main global coffee producer region, accounting for more than 56% of the world production of Arabica coffee (FAOSTAT, 2021). In this region, the coffee leaf miner *Leucoptera coffeella* (Guérin-Méneville) (Lepidoptera: Lyonetiidae) is one of the key coffee pests (Lomelí-Flores et al., 2010; Reis and Souza, 1996; Souza et al., 1998). This microlepidopteran has an adult life span of 2-3 weeks (Souza et al., 1998), and it can reach 12 annual generations depending on climatic variables (Reis and Souza, 2002). The adults lay eggs on the leaf surface, and after the eggs hatching, the young larvae penetrate the leaf epidermis, feeding exclusively on the parenchyma (Reis and Souza, 1996; Souza et al., 1998). Due to the presence of the pest, there is a reduction in photosynthetic capacity, early senescence of leaves, decrease in productivity and coffee berrys quality (Fragoso et al., 2003; Reis and Souza, 2002; Souza et al., 1998). Therefore, depending on the infestation levels of *L. coffeella*, productivity can decrease by around 50 to 87% (Dantas et al., 2021; Leite et al., 2021; Motta et al., 2021; Ramiro et al., 2004).

Several factors can influence the field's dynamic population of *L. coffeella*. These factors are climatic elements, natural enemy populations, plant characteristics, and spacing between plants (Dantas et al., 2021; Medeiros et al., 2019; With and Crist, 1995). Climatic elements can affect pests' mortality, development, reproduction, and dispersion (Fernandes et al., 2009; Fidelis et al., 2019; Pereira et al., 2007a). Natural enemies are the main cause of pest mortality in crops due to feeding on pests (Pereira et al., 2007a; Pereira et al., 2007b). The host plant's nutritional quality and morphology traits interfere with pest development, contributing to the increase or decrease of pest populations in the field (Bernays and Chapman, 1994; Farias et al., 2020; Lima et al., 2018).

The distribution and dispersion of pests may be related to the abovementioned factors. Therefore, relying on prior knowledge of areas and seasons of higher incidence of *L. coffeella* causing economic losses to farmers is essential. It helps in elaborating a specific integrated pest management program for the region (Alves et al., 2011; Galdino et al., 2017; Ramos et al., 2019)

Using integrated pest management principles, the precise and correct management of *L. coffeella* begins with the early detection of the pest, sampling, and determination of the pest's spatial distribution and dispersion pattern in the field (Alves et al., 2011; Sciarretta and Trematerra, 2014). Geostatistics is a tool used in precision agriculture that allows the description of these patterns (Barrigossi et al., 2001; Martins et al., 2018; Oliver, 2010; Rosado et al., 2015; Veran et al., 2015).

In addition to sampling, integrated pest management programs also use control levels in decision-making to control or not the pest in the field (Ehler, 2006; Paulo Arcanjo et al., 2021; Pedigo et al., 1986). Sampling and control levels are essential in designing decision-making systems (Ehler, 2006). These systems differ from conventional agriculture because they consider the population density of the pest and its distribution within the crop.

Therefore, the objectives of this study were: (i) to assess the seasonality of the *L. coffeella* population and the factors that regulate its population dynamics in the *Coffea arabica* crops located in two distinct geographic regions; (ii) to assess the spatial-temporal distribution of *L. coffeella* in coffee crops located in one of the largest commercial coffee-producing regions in the Brazilian Cerrado and (iii) to propose decision-making systems to control *L. coffeella* in coffee crops using management zones.

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CHAPTER 1: SEASONAL VARIATION OF *Leucoptera coffeella* POPULATION DYNAMIC IN *Coffea arabica* FIELDS FROM THE ATLANTIC FOREST AND THE CERRADO BIOMES

ABSTRACT

The Neotropical region is the main coffee producer area, and Brazil is the larger producer, where coffee is cultivated mainly in regions of the Atlantic Forest and Cerrado biomes. The coffee leaf miner, *Leucoptera coffeella* (Lepidoptera: Lyonetiidae), is one of the main pests of coffee in the Neotropical region, and it can lead to substantial economic losses. The first step in managing *L. coffeella* is to understand its spatiotemporal dynamics. Thus, this research aims to assess the seasonality of the *L. coffeella* population and the factors that regulate its dynamics on coffee crops in the Atlantic Forest and the Cerrado biomes. The study was carried out over four years at seven different locations. Three sites were located in the Cerrado, and four areas were located in the Atlantic Forest. The data were collected from Procafé Foundation and from Milano Farm - Agricultural Olam Coffee. The damage of *L. coffeella* was higher in the Cerrado when compared to the Atlantic Forest areas. In the Cerrado, the air temperature and the potential evapotranspiration were higher, while the rainfall was lower. Pest population peaks of 100% active mined leaves occurred between July and October, all the years evaluated, when coffee plants were at fruiting and flowering stages. The minimum, optimal and maximum temperatures for pest development were 16.59, 26.81, and 34.8°C, respectively. Therefore, the biome and climatic elements influenced the spatiotemporal dynamics of L. coffeella. Based on our results, the Cerrado biome showed more suitable climatic conditions for L. coffeella development. This information is essential for designing and implementing efficient control strategies, as further discussed.

Keywords: Coffee Leaf miner. Evapotranspiration. Rainfall. Population Fluctuation. Temperature.

1. INTRODUCTION

Coffee is one of the biggest commodities in the world (Avelino et al., 2018). According to the World Coffee Organization, world production reached 170 million tons in 2018/2019 (ICO, 2019). Besides its economic importance, coffee production has an important social role in the countries where it is cultivated. It is estimated that 125 million people depend on this crop for their livelihood (Avelino et al., 2018). Although more than a hundred species are known, only *Coffea arabica* L. (Arabica coffee) and *Coffea canephora* (Robusta or Conilon) are commercially important (Davis et al., 2006). Arabica coffee accounts for 60% of global coffee production and is highly appreciated because of its superior organoleptic properties compared to Robusta coffee (Aerts et al., 2017).

The Neotropical region is the world's main coffee producer, responsible for 56.48% of world production (FAOSTAT, 2021). In this region, the coffee leaf miner, *Leucoptera coffeella* (Guérin-Mèneville & Perrottet) (Lepidoptera: Lyonetiidae), is one of the main pests of the crop (Lomelí-Flores et al., 2010; Reis and Souza, 1996; Souza et al., 1998). *Leucoptera coffeella* is a nocturnal half-light moth with an adult life span of 2-3 weeks (Souza et al., 1998). Depending on air temperature, there may be up to 12 generations per year (Reis and Souza, 2002). Adults lay eggs on the leaf surface, and after the eggs hatch, the young larvae penetrate the leaf epidermis feeding exclusively on the parenchyma (Reis and Souza, 1996; Souza et al., 1998). These mines created by the pest reduce photosynthesis, cause early leaf senescence, and consequently lower productivity and beverage quality (Fragoso et al., 2003; Reis and Souza, 2002; Souza et al., 1998).

Integrated pest management programs rely on prior knowledge of areas and seasons of the highest risk of pest problems. This information enables us to guide the sampling process and choose the appropriate control methods for a given situation (Alves et al., 2011; Galdino et al., 2017; Ramos et al., 2019). Climatic elements, natural enemy populations, and plant characteristics are factors that may affect the seasonal variation of pests (Medeiros et al., 2019; With and Crist, 1995). Climatic elements can affect pests' mortality, development, reproduction, and dispersion (Fernandes et al., 2009; Fidelis et al., 2019; Pereira et al., 2007a). Natural enemies are the main cause of pest mortality in crops due to feeding on pests (Pereira et al., 2007a; Pereira et al., 2007b). Conversely, host plant traits such as nutritional quality and morphology interfere with pest development and subsequently contribute to increasing or decreasing pest populations in the field (Bernays and Chapman, 1994; Farias et al., 2020; Lima et al., 2018).

In Brazil, coffee is grown in regions located in different biomes. The Brazilian biodiversity is distributed into six biomes: Amazon Forest, Caatinga, Cerrado, Atlantic Forest, Pantanal and Pampas (IBGE, 2020). Each biome has distinct geographical and biodiversity characteristics, implying climate variation (Penereiro et al., 2018). Currently, the largest Arabica coffee growing areas are distributed in the Atlantic Forest and Cerrado biomes. The first is a biome with a great richness of fauna and flora species (Scolforo et al., 2015). According to the Köppen-Geiger classification, this biome is denominated Humid Subtropical Zone, characterized by a rainy summer and a dry winter. Annual rainfall exceeds 2000 mm (Morellato et al., 2000). The temperature in the coldest months can reach 0°C, while summer temperatures may exceed 22°C (Alvares et al., 2013). Cerrado is the largest Brazilian biome after the Amazon Forest. It is one of the richest biomes in biodiversity in the country (Myers et al., 2000; Scolforo et al., 2015; Werneck et al., 2012). According to the Köppen-Geiger classification, Cerrado was located in the Tropical Zone. This zone is characterized by distinct dry and rainy periods with a dry winter and humid summer season (Alvares et al., 2013). It has an average rainfall of 750 mm to 1250 mm (Farmer and Cook, 2013) and a temperature above 18°C throughout the year (Alvares et al., 2013; Fernandes et al., 2012). Therefore, Cerrado is considered a warmer and dryer biome, and Atlantic Forest is humid with moderated temperatures.

Despite the importance of *C. arabica* and its main pest, *L. coffeella*, there are no studies on the seasonal variation of this herbivore correlating it with the Cerrado and Atlantic Forest biomes. Brazil's largest coffee-producing regions are located and distributed in these two biomes. In addition, these biomes have different climatic and biodiversity characteristics that may influence the seasonality of *L. coffeella* in coffee crops. Therefore, the objective of this study was to assess the seasonality of the *L. coffeella* population and the factors that regulate its population dynamics in the *C. arabica* crops located in the Atlantic Forest and the Cerrado biomes.

2. MATERIAL AND METHODS

2.1 Experimental conditions

The densities of *L. coffeella* were evaluated in four Arabica coffee crops in the Atlantic Forest biome and three areas in the Cerrado biome monthly from March 2016 to December 2019. The crops evaluated in the Atlantic Forest were located in the municipalities of Boa Esperança, Carmo de Minas, Muzambinho, and Varginha in the state of Minas Gerais (Figure 1). The crops in the Cerrado were located in Franca, São Paulo State; Araguari, Minas Gerais State; and Barreiras, Bahia State. Catuaí and Mundo Novo varieties are used, and both are susceptible to *L. coffeella*. The crops located in Araguari and Barreiras are sprinkler irrigation systems. These irrigation systems do not influence the biology of *L. coffeella* since the larval stage occurs inside the leaf, below the leaf epidermis. All the crops have between 10 to 20 years of production and are mechanized. Fields were classified into biomes according to the IBGE classification (2020). These areas represent the main coffee-producing areas in Brazil. The distribution of coffee fields in each biome is shown in Figure 1.

2.2 Data Sampling

Arabica coffee plants were divided into three strata: apical, median, and basal, for sampling leaves in the field. Leaves from the middle and the apical stratum were used in the assessments because they harbor the major densities of the pest (Reis and Souza, 1996). The density of *L. coffeella* was determined by counting the number of leaves with active mines (i.e., containing alive larvae). To quantify the percentage (%) of *L. coffeella* infestation in each field, the equation (1) was used:

$$\% \; L. coffeella \; infestation = \left(\frac{number \; of \; leaves \; with \; live \; larvae}{total \; number \; of \; sampled \; leaves}\right) * 100 \qquad (1)$$

The *L. coffeella* densities data were collected during all coffee plant stages. The densities of *L. coffeella* from Franca, Varginha, Carmo de Minas, Boa Esperança, Muzambinho, and Araguari were obtained through monthly bulletins issued by the Fundação Procafé (http://fundacaoprocafe.com.br/). To calculate the population density of these places, pairs of leaves of 20 to 30 plants per field were collected. To calculate the densities of *L. coffeella* of the Barreiras, leaves were collected from 100 plants per pivot in a total of 1800 plants. These data were obtained directly from Fazenda Milano - Agrícola Olam Coffee.

2.3 Climatic data

Temperature, rainfall, and evapotranspiration data were obtained from the meteorological stations located in each field mentioned above. Data from the fields of Franca, Muzambinho, Araguari, Boa Esperança, Carmo de Minas, and Varginha were compiled from the monthly bulletins obtained from the Procafé Foundation. The weather stations were of type Vantage Pro2 Davis (K6162) in Procafé locations. The data from the coffee field in Barreiras were acquired at the crop meteorological station of Milano Farm. Monthly average temperature, monthly accumulated rainfall, and the potential monthly-accumulated evapotranspiration data were used in the data analysis.

2.4 Data analysis

The monthly rate of population increase (MRPI) was calculated according to the ideal temperatures for the development of *L. coffeella,* the net reproductive rate of population increase (R_0), and generation time (T) determined by Giraldo-Jaramillo (Giraldo-Jaramillo et al., 2019). The monthly rate of population increase ($MRPI$) was calculated according to equation (2):

$$MRPI_t = \frac{(30 \times R_0)}{T} \quad (2),$$

where $MRPI_t$ is the monthly rate of pest population increase at temperature t, $R_0$is the reproductive rate, and *T* is the generation time (days).

The monthly population growth rate (MRPI) was calculated regardless of location and biome. This is possible because the minimum, optimal and maximum temperature for the development of the *L. coffeella* does not change according to crops are located. The $MRPI_t$ data as a function of air temperature were subjected to regression analysis (α = 0.05). This model was selected based on the following criteria: (i) statistical significance (P < 0.05), (ii) biological significance, (iii) highest regression coefficient (R^2), and (iv) model simplicity (Damos and Savopoulou-Soultani, 2012; Martins et al., 2016). The minimum development temperatures were those in which *L. coffeella* presented $MRPI_t$ = 1, whereas the optimal development temperature was the one in which *L. coffeella* had maximum $MRPI_t$.

Population density curves were made for each location and year studied using the densities of *L. coffeella*, air temperature data (minimum, average, and maximum), precipitation, potential evapotranspiration, and the thermal limits for this pest. The relationship between the density of *L. coffeella* and the explanatory variables (climatic elements) in each biome (Atlantic Forest and Cerrado) was determined. The climatic elements and the L. coffeella densities were compared using each variable's means and standard errors. The densities of *L. coffeella* in the Cerrado and Atlantic Forest for each year were compared using the F-test.

The density data of *L. coffeella* was subjected to multiple linear regression analysis (α = 0.05) as a function of average air temperature, rainfall, and potential evapotranspiration using PROC REG from SAS Software (SAS 2009).

3. RESULTS

Significant differences (*P* < 0.05) were observed in *L. coffeella* densities, average air temperature, rainfall, and potential evapotranspiration between coffee fields grown in the two biomes.

In the four years of this study, the mean densities of *L. coffeella* in coffee fields located in the Cerrado were higher than in the Atlantic Forest (Figures 2, 3, and 4). In the Cerrado crops, the highest densities of the pest generally occurred between July and October, all the years evaluated, when coffee plants were at the fruiting and flowering stages (Figure 3).

The minimum, optimal, and maximum development temperatures for *L. coffeella* were 16.59, 26.81, and 34.87°C, respectively (Figure 5). The multiple linear regression model of the percentage of leaves mined by *L. coffeella* as a function of average air temperature, rainfall, and potential evapotranspiration was significant ($F = 23.15$ and $P < 0.0001$). The average air temperature and potential evapotranspiration showed a positive and significant relationship with the density of *L. coffeella*. The rainfall significantly and negatively correlated with *L. coffeella* density (Table 1).

4. DISCUSSION

There are differences in the *L. coffeella* densities between the Atlantic Forest and the Cerrado biomes. In the coffee fields located in the Cerrado, the percentage of infestation of *L. coffeella* frequently exceeded 30%. In contrast, the percentage of infestation of *L. coffeella* in fields located in the Atlantic Forest biome has always been lower than 20% of active mined leaves. This result is helpful information for the integrated pest management programs of *L. coffeella* since the economic injury level (EIL) adopted for this pest corresponds to 30% of active mined leaves (D'Auria et al., 2016; Fidelis et al., 2019; Reis and Souza, 2002; Souza et al., 1998). Therefore, the population of *L. coffeella* in the Cerrado biome frequently exceeds the EIL (30%).

Considering *L. coffeella* as one of the main pests of coffee crops, special attention should be given to developing management programs for regions such as the

Cerrado biome, which has highly suitable conditions for developing *L. coffeella*. Additionally, since there are marked differences in the pest density in each biome, region-specific sampling plans must be developed for *L. coffeella*.

Differences in the seasonality of *L. coffeella* were also detected. The highest densities occurred when coffee plants were at the flowering and fruiting stages. We observe that crops with the highest densities of *L. coffeella* are in Araguari and Barreiras, both irrigated crops. Coffee fields in the Cerrado are generally irrigated, and, to promote the standardizing of the flowering and maturation of coffee berries, the practice of water deficit is usually applied (Fernandes et al., 2012; Fernandes et al., 2009). This practice, in turn, favors the attack of *L. coffeella* (Fernandes et al., 2012; Meireles et al., 2001). Another aspect is the trade-off between investing energy for reproduction or defense. Since the plant mobilizes nutrients and water for flower formation and coffee berry maturation, the content of defense compounds available in the plant tissues decreases, thereby making the coffee plants more susceptible to *L. coffeella* (Meireles et al., 2001; Meireles et al., 2009).

Air temperature, rainfall, and potential evapotranspiration were significantly different between these two biomes, while no significant differences were detected in the altitudes. In this context, higher densities of *L. coffeella* were observed in time, areas of higher air temperature, potential evapotranspiration, and lower rainfall. Temperature is known to, directly and indirectly, influence insect populations (Lomelí-Flores et al., 2010; Martins et al., 2016). Directly affects the reproduction rate, development time, voltinism, and genetic composition in insects (Assis et al., 2012; Bale et al., 2002; Giraldo-Jaramillo et al., 2019). Thus, temperature influences the number of *L. coffeella* generations per year. High temperatures, such as those found in the Cerrado fields, might explain the higher infestation of the *L. coffeella* in this biome (Androcioli et al., 2018; Caffarra et al., 2012).

Indirectly, the temperature can influence the quality of host plants, especially with respect to substances used in chemical communication (Awmack and Leather, 2002; Ayres and Lombardero, 2000). Substances of secondary metabolism in plants can be toxic, stimulant, repellent, or attractive to insects (Kollberg et al., 2015). Some secondary compounds in coffee, such as phenolic compounds (caffeic and chlorogenic acids) and alkaloids (caffeine and methylxanthines), are present in greater quantities in young leaves (Ashihara, 2006). Young leaves of the middle and apical section of the coffee plant are also generally preferred for *L. coffeella* oviposition (Ramiro et al., 2004; Righi et al., 2013). In this sense, caffeine, one of the main compounds present in the leaves, may also act as a stimulant for egg-laying or suppress some repellent compound (Magalhães et al., 2008a; Magalhães et al., 2008b).

The lower, optimal, and upper thermal thresholds can be defined as the minimum, optimal and maximum temperatures necessary for *L. coffeella* to complete its life cycle (Ghini et al., 2008; Martins et al., 2016). The thermal thresholds obtained in this work corroborate those of the *L. coffeella* fertility life table published by Giraldo-Jaramillo et al. (2019), except for the lower development temperature, which was 2ºC lower than reported. We observed that average air temperature in the Cerrado crops remained above the lower thermal threshold for the development of *L. coffeella*, thereby providing continuous development of the species throughout the year. Because Cerrado fields are conducted under full sun, the average air temperature in the coffee plantation is continuously high, consequently favoring the attack of *L. coffeella* (Lomelí-Flores et al., 2010; Righi et al., 2013). In the Atlantic Forest, at some periods of the year, the temperature was below the lower threshold of development for *L. coffeella*, especially at night (Fauset et al., 2018; Maia et al., 2010).

The rainfall also significantly affects the population dynamics of the insects (Bacci et al., 2018; Pereira et al., 2007a). Rain is directly related to mortality due to dislodgment and unviability of eggs and the mortality of larvae by asphyxiation due to the flooding of mines on coffee leaves (Bacci et al., 2018; Medeiros et al., 2019; Nestel et al., 1994; Pereira et al., 2007a). In addition, rainfall can interfere with reproduction affecting the adult's flight and mating (Bacci et al., 2018; Michereff et al., 2004). Indirectly, rain can negatively affect *L. coffeella* due to the physiological disturbances caused to interfere with the chemical composition of the plant and the population dynamics of natural enemies, especially predatory wasps and parasitoids (Lomelí-Flores et al., 2010; Pereira et al., 2007a).

The potential evapotranspiration is another climatic variable that significantly affects the density of *L. coffeella*. It is defined as the process of water loss by plant transpiration and soil evaporation (Silva et al., 2011). Cerrado fields had higher evapotranspiration when compared to Atlantic Forest crops (Fig. 4). The Araguari and Barreiras fields that showed the highest *L. coffeella* densities are irrigated. Therefore, they have a higher amount of water available to the plant. High water content in the leaves reduces the temperature and the vapor pressure, making the growth of *L. coffeella* inappropriate (Righi et al., 2013). However, the population peaks of the pest occurred in periods of low rainfall, high temperature, and the period of water deficit, as aforementioned.

In addition to climatic factors, the relief and the vegetation type can interfere in the *L. coffeella* dispersion. Cerrado relief is usually composed of a "chapada," a plateau in the Brazilian highlands. It presents arboreal, bush, and underwood vegetation, providing adequate conditions for *L. coffeella* dispersion. Atlantic Forest, in turn, is composed of arboreal vegetation, plateaus, and especially large mountain ranges, which can negatively affect insect dispersion (IBGE, 2020; IBGE, 2009; Martins et al., 2018).

In conclusion, the population dynamics of *L. coffeella* are influenced by the climatic elements of each biome. The coffee fields cultivated in the Cerrado biome have higher infestations of *L. coffeella* than those from the Atlantic Forest biome, especially when coffee plants are at flowering and early fruiting stages. Coffee fields cultivated in the Cerrado under higher temperature and potential evapotranspiration and lower rainfall present higher suitability to *L. coffeella*, thereby having a higher potential to reach high population levels and stay above EIL. The population density of *L. coffeella* did not reach the EIL in the period evaluated in the coffee crops cultivated in the Atlantic Forest. However, *L. coffeella* occurs in Cerrado fields throughout the year, and the population peaks between July and October, when the population exceeds EIL. Therefore, coffee crops in the Cerrado need to be evaluated more frequently than fields in the Atlantic Forest. Furthermore, the control methods must be applied quickly as *L. coffeella* often reaches EIL in Cerrado fields. This knowledge supports improving pest management programs by increasing control efficiency and reducing pesticide use, consequently minimizing costs and environmental impacts.

Acknowledgments

We are grateful for the financial support provided by ‘Conselho Nacional de Desenvolvimento Científico e Tecnológico’, the ‘Coordenação de Aperfeiçoamento de Pessoal de Nível Superior’, Finance Code 001, and the ‘Fundação de Amparo à Pesquisa do Estado de Minas Gerais’ (FAPEMIG). Special thanks to Olam Coffee for providing financial support and data and the Procafé Foundation (http://fundacaoprocafe.com.br/) for the data for this research.

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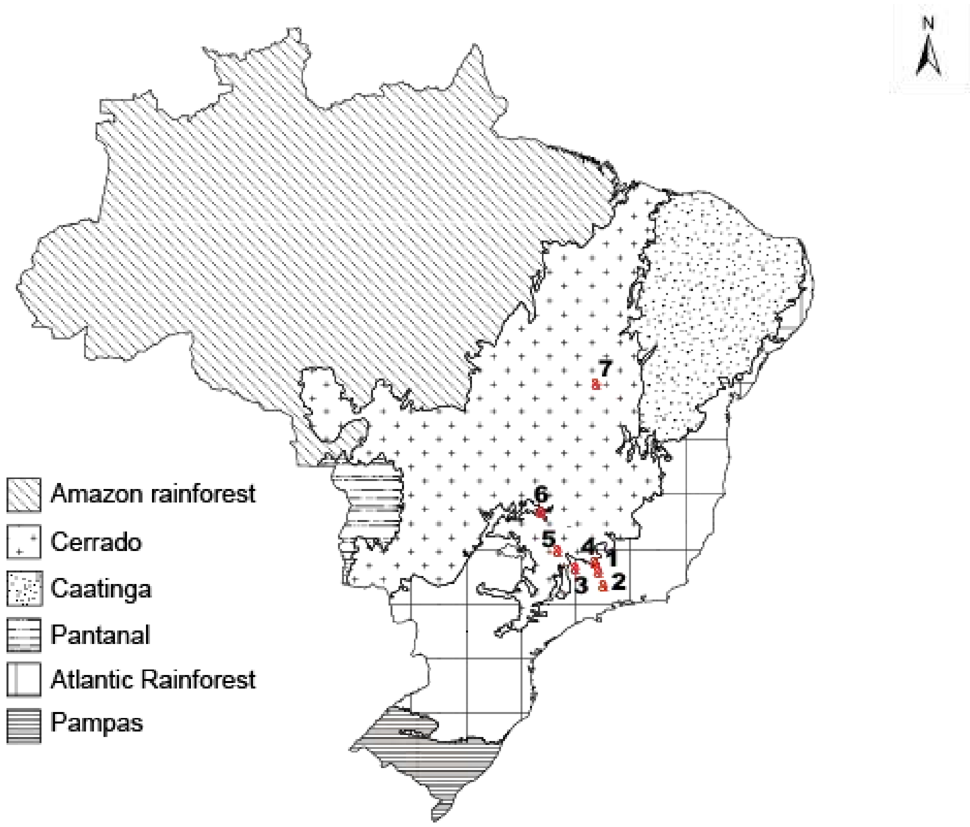

Sampling sites	Geographic coordination	Altitude(m)	Biome
1 - Boa Esperança - MG	45°34'37"W, 21°03'59"S	830	Atlantic Rainforest
2 - Carmo de minas - MG	45°09'03"W, 22°10'31"S	1080	Atlantic Rainforest
3 - Muzambinho - MG	46°32'04"W, 21°20'47"S	1285	Atlantic Rainforest
4 - Varginha - MG	45°24'22"W, 21°34'00"S	940	Atlantic Rainforest
5 - Franca - SP	47°24'33"O, 20°28'19"S	1025	Cerrado
6 - Araguari - MG	48°12'25"W, 18°33'21.9"S	933	Cerrado
7 - Barreiras - BA	45°30'29.44"W, 12°18'16.04"S	688	Cerrado

Figure 1 - Illustration of Brazil map with the biomes delimitation and sampling locations of *Leucoptera coffeella* field populations in coffee crops in Brazil. Biomes were classified according to IBGE (2020).

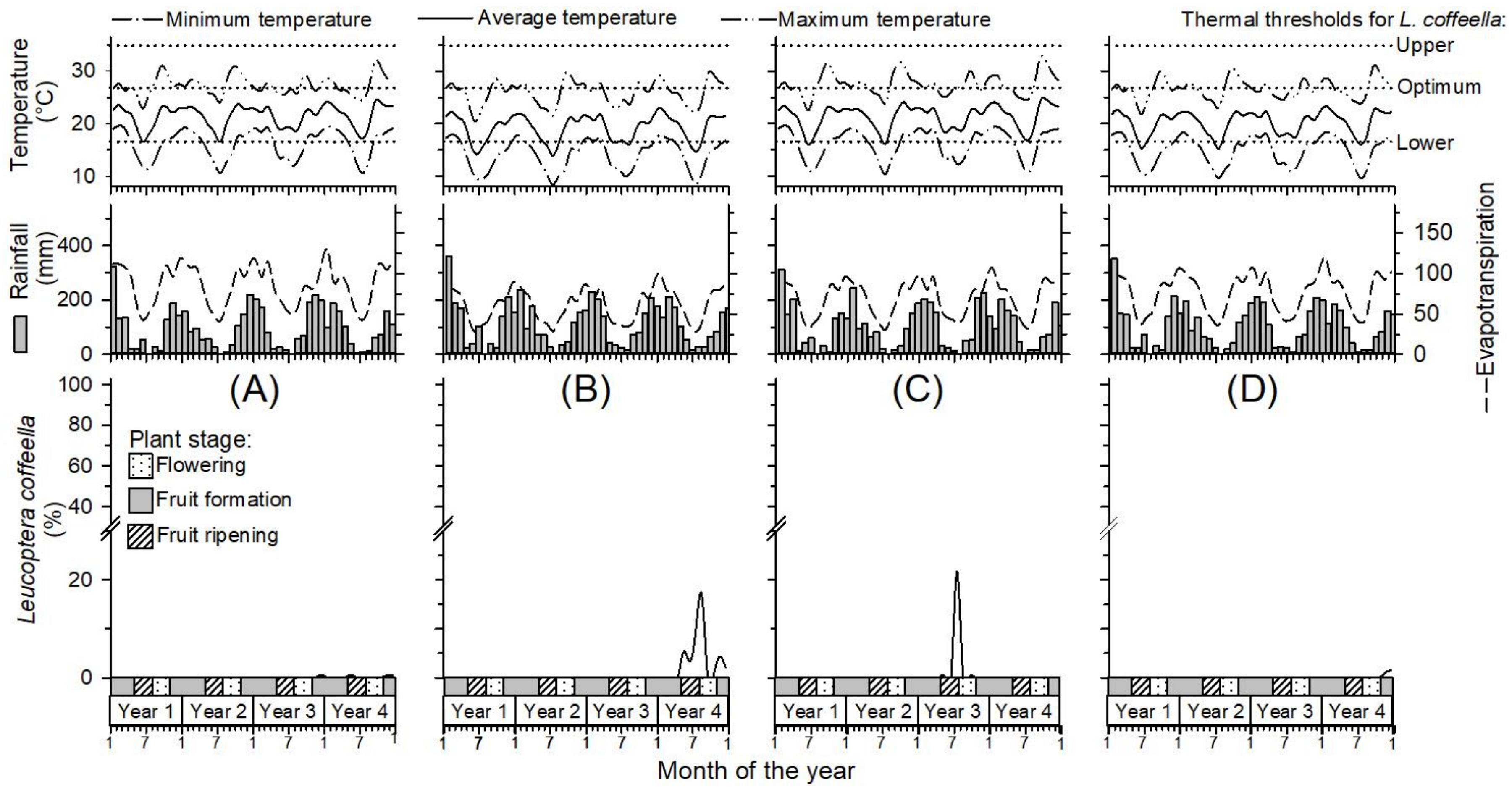

Figure 2 - Seasonal variation of air temperature (°C), rainfall (mm. month^{-1}), evapotranspiration (mm. month^{-1}), and density of *Leucoptera coffeella* over four years in four locations in the Atlantic Forest biome: (A) Boa Esperança, (B) Carmo de Minas, (C) Muzambinho and (D) Varginha. Arabic numerals indicate the month of the year (1 = January and 7 = July).

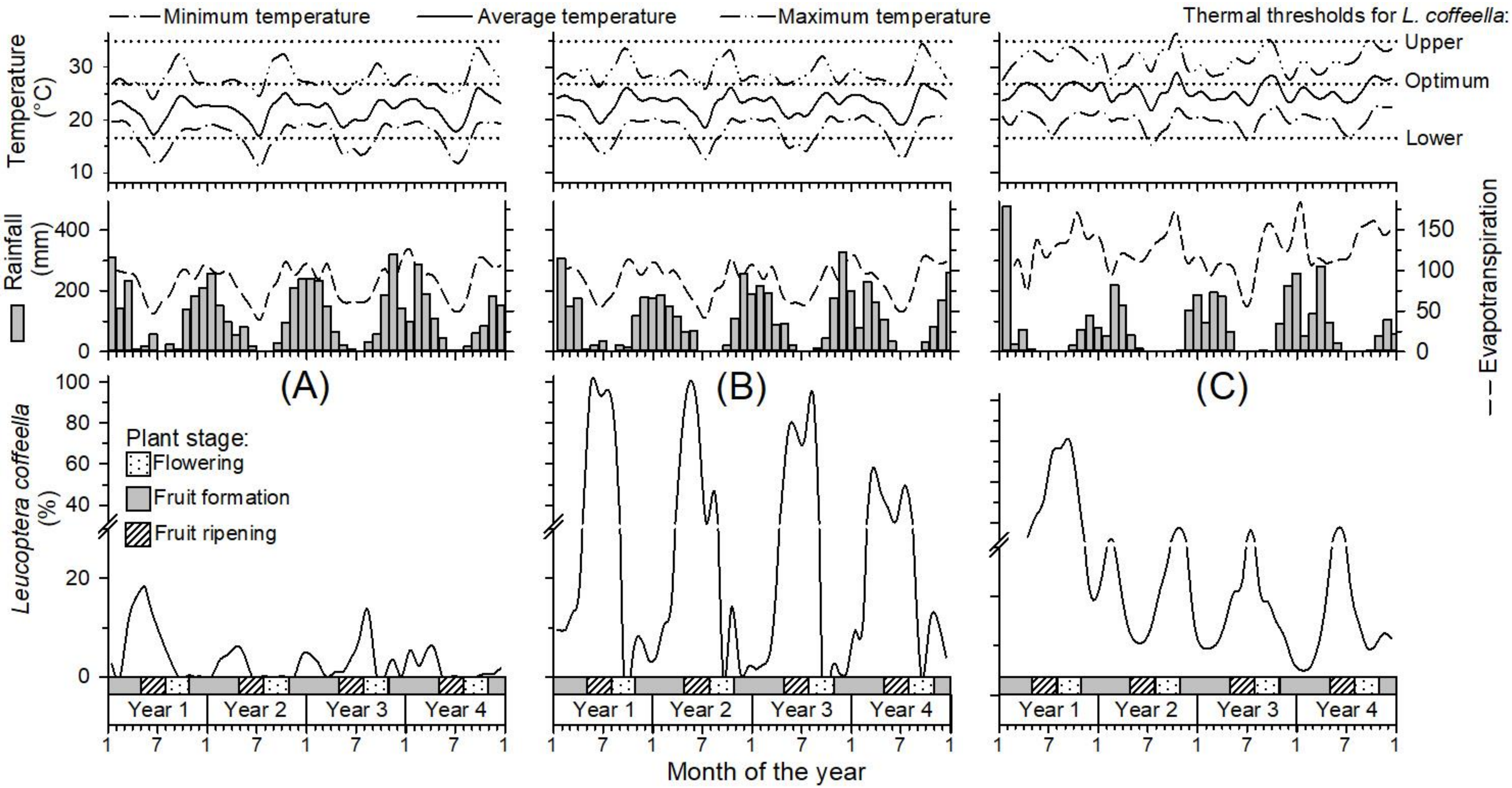

Figure 3 - Seasonal variation of mean air temperature (°C), rainfall (mm. month^{-1}), evapotranspiration (mm. month^{-1}), and *Leucoptera coffeella* density over four years in three locations in the Cerrado biome: (A) Franca, (B) Araguari and (C) Barreiras. Arabic numerals indicate the month of the year (1 = January and 7 = July).

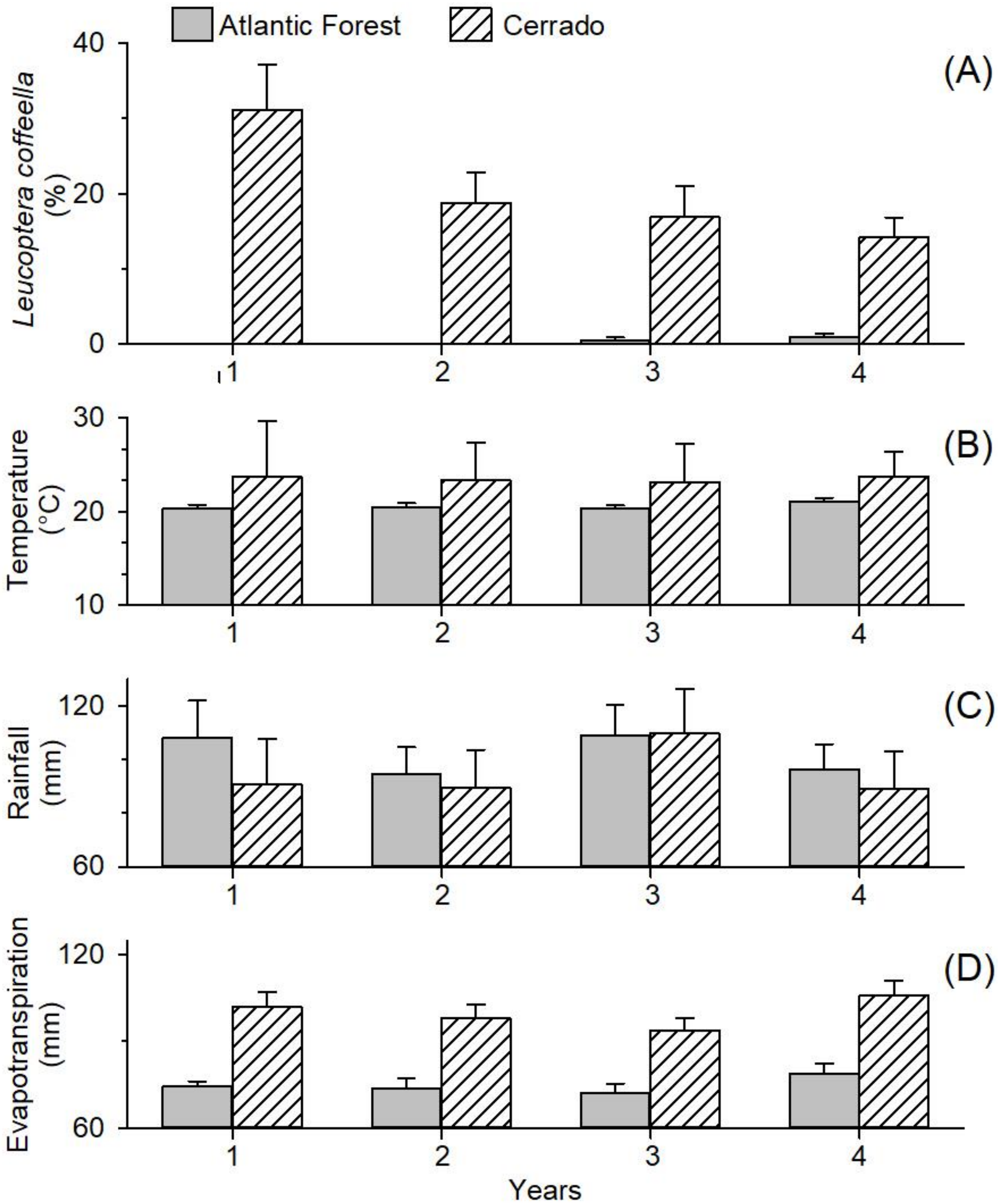

Figure 4 - Variation (mean ± standard error) of (A) densities of *Leucoptera coffeella*, (B) average air temperature (°C), (C) rainfall (mm. month^{-1}), (D) evapotranspiration (mm. month^{-1}) in coffee fields located in the Atlantic Forest and Cerrado biomes over four years.

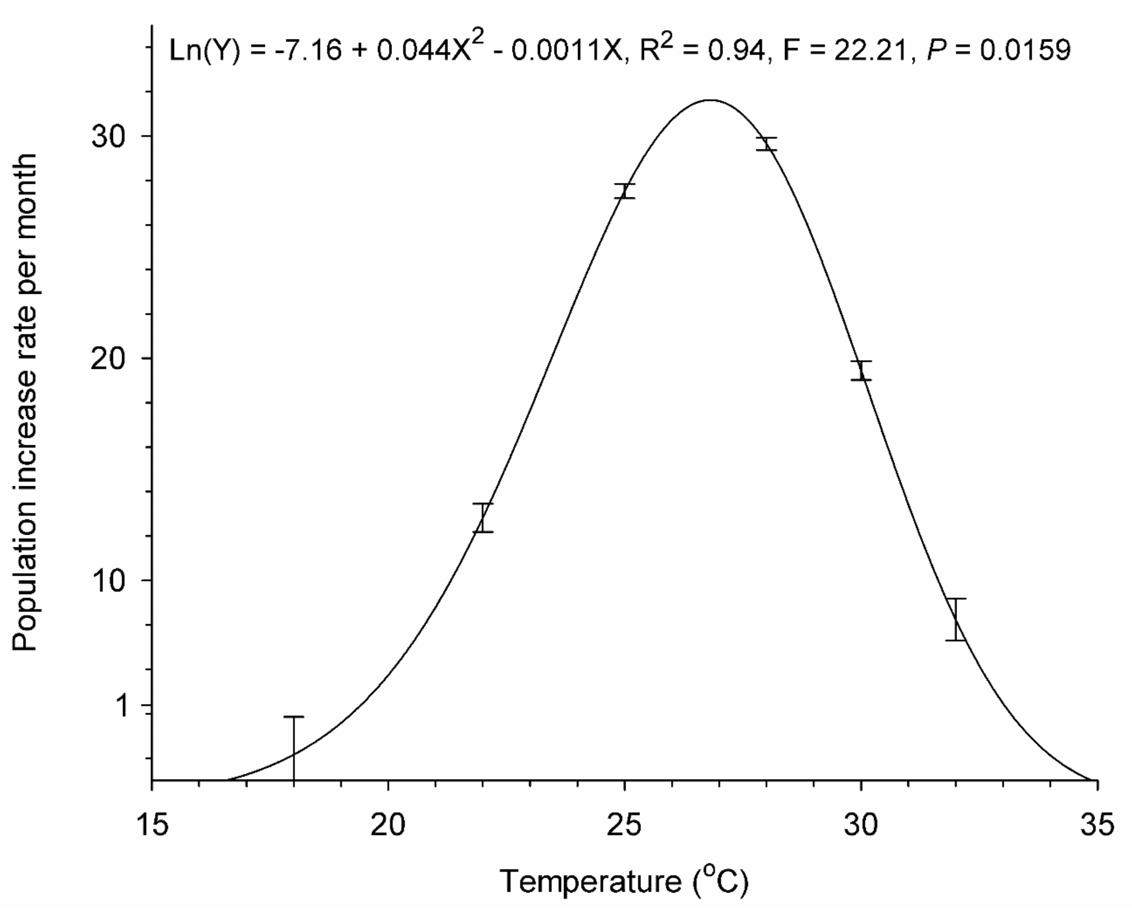

Figure 5 - The monthly rate of population increases (generation.month) for *Leucoptera coffeella* as a function of air temperature. The vertical line segments are the confidence intervals at a 95% probability. This model was built for both biomes.

Table 1 - Angular coefficients of multiple linear regression (R^2 = 0.18, F = 23.15, and *P* < 0.0001) of the percentage of coffee leaves mined by *Leucoptera coffeella* as a function of average air temperature, rainfall, and potential evapotranspiration.

Independent variable	Angular coefficients
Average air temperature (°C)	3.73*
Rainfall (mm. $month^{-1}$)	-0.079*
Potential evapotranspiration (mm. $month^{-1}$)	0.17*
Constante	-50.49

* Significant by the F test at *P <0.05*. The analysis does not consider the biome.

CHAPTER 2: USE OF GEOSTATISTICS AS A TOOL TO STUDY SPATIAL-TEMPORAL DYNAMICS OF *Leucoptera coffeella* IN COFFEE CROPS

ABSTRACT

Coffee is considered one of the most important commercial commodities globally, and in 2020 it moved a global market of US$ 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. Besides, 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 years (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. Also, 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. During three years, the colonization started at the edge of the crop. The sampling should be done equidistant as the pest is distributed equally in all directions. The information found in this study provides useful 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

1. INTRODUCTION

Coffee is considered one of the largest commodities trades in the world, and it holds a significant share of global agribusiness (Alves and Lindner, 2020; Avelino et al., 2018; Lomelí-Flores et al., 2010; Vegro and Almeida, 2020). Its production is of great economic and social importance in the countries where it is grown (Avelino et al., 2018), which represented a global market of 102.02 billion dollars in 2020 (Intelligence, 2021). However, the attack of pests in coffee production can cause great economic losses (Avelino et al., 2018; Leite et al., 2021; Rosado et al., 2021).

The coffee leafminer *Leucoptera coffeella* (Guérin-Méneville) (Lepidoptera: Lyonetiidae) is pest critical in coffee-producing countries, especially in Neotropical regions (Dantas et al., 2021; Leite et al., 2020b; Pantoja-Gomez et al., 2019; Tuelher et al., 2003). This microlepidopteran causes damage in the immature phase due to the feeding on the leaf parenchyma. This damage reduces the leaf area and photosynthetic capacity and occurs premature leaves' senescence, leading to reductions in the yield and quality of the coffee berries (Souza et al., 1998). Therefore, depending on the infestation levels of *L. coffeella*, productivity can decrease by around 50 to 87% (Dantas et al., 2021; Leite et al., 2021; Motta et al., 2021; Ramiro et al., 2004).

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 (Alves et al., 2011; Oliver, 2010; Scalon et al., 2011). This knowledge is important since it allows us to carry out effective, low-cost, and environmentally friendly control measures (Barrigossi et al., 2001; Martins et al., 2018).

Geostatistics is a tool that allows one to describe the dispersal patterns and the spatial distribution of pests in the field (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 (Barrigossi et al., 2001; Veran et al., 2015).

Despite the severe damage caused by *L. coffeella* on coffee crops, there are few studies about this pest's decision-making process, especially considering its spatial distribution pattern. Thus this research aimed to assess the spatiotemporal 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. MATERIAL 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, in 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 (Leite et al., 2020a; Leite et al., 2020b; Leite et al., 2021). Eighteen central pivots of 100 hectares were assessed, with a total area of 1.800 hectares. Figure 1B and TableTable 1 show the locations and characteristics of the 18 central pivots. The plant spacing in the assessed coffee crops was 3 x 1 m, and the sprinkler irrigation system was done via a central pivot. Also, it was used the application of the fungicides Pyraclostrobin, Thiophanate-methyl, Azoxystrobin, and Cyproconazole to control the Rust (*Hemileia vastatrix*), Cercosporiosis (*Cercospora coffeicola*) and Phoma Spot (*Phoma costaricensis*); and the insecticides Abamectin, Thiamethoxam, Chlorantraniliprole, and Novalurom.

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 (Reis and Souza, 1996; Souza et al., 1998). 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 (500m) was measured, and an additional 500m was added for a total of 1,000m 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 calculated the percentage of vegetation around each pivot was 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 (Google Earth Pro, 2021) (Figure 2).

2.3 Statistical analysis

2.3.1 Correlation analysis

Correlation analysis using the PROC CORR procedure of the SAS (SAS Institute 2013) 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 (ESRI, 2016). Initially, very discrepant data from the others (outliers) were removed to reduce errors in the semivariogram results and in the interpolations (Li and Heap, 2011; Park et al., 2012)

Subsequently, semivariograms were estimated using circular, spherical, exponential, and Gaussian models. For each evaluation date, the selected model was the one with 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 (Isaaks and Srivastava, 1989; Ramos et al., 2019).

The presence of anisotropy was also tested for the following directions: 0º, 45º, 90º, and 135º directions. For each of these models, the nugget effect (C_0= measure of sample error), sill (C= maximum value of semivariance in dependent samples), and range (A_0=distance beyond which there is no spatial correlation) were determined (Gumprecht et al., 2009).

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

$RSD = \frac{C_0}{C_0 + C}$, where: C_0 = nugget effect e $(C_0 + C)$ = still.

The spatial dependence of each semivariogram was classified as strong when RSD ≤ 0.25, moderate between 0.25 and 0.75, and weak when RSD > 0.75 (Ramos et al., 2019; Sciarretta and Trematerra, 2006).

The ordinary kriging method was used to interpolate and estimate the density of *L. coffeella* in the non-sampled pivot areas. Cross-validation was used to verify the quality of estimates obtained by the kriging models (Martins et al., 2018; Ramos et al., 2019). 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 (β_0) and the sum of squared residue (RSS), and the highest coefficients of determination (R^2) and slope of the curves of the models (β_1). All 47 selected models showed plateau and nugget effect; 26 were spherical, 13 were Gaussian, seven were exponential, and one was circular. From the 47 selected models, 45 showed strong spatial dependence (RSD < 0.25) and two moderate spatial dependence 0.25 ≤ RSD ≤ 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 four were anisotropic. The anisotropic models showed greater amplitude in 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). On the other hand, 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 called 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 different locations inside pivots of 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 eastern region of the area

(Figures 3 and 4). While in the fourth year, it appeared in the central area of the coffee crop (Figure 4).

6. 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 (Taylor, 1984). The spatial distribution of insects is considered aggregated when there is spatial data dependence between the sampled points (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 (Alves et al., 2011; Bacca et al., 2006). Identifying aggregation areas allows control measures to be applied assertively in pest hotspots, reducing insecticides and pest dispersion in crops (Lima et al., 2018).

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 for pest management (Ifoulis and Savopoulou-Soultani, 2006). Based on the range is possible to determine the spacing of pheromone baited (Bacca et al., 2006) 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; (Carvalho et al., 2020; Kirwan et al., 2005). So this should avoid the miscalculation of population estimates (Carvalho et al., 2020).

The high range found in this work is due to the high flight capacity and dispersion of *L. coffeella* (Bacca et al., 2006). 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 work can be expanded to the entire Cerrado coffee region. In addition, studying distances between samples smaller than those used in this work can refine sampling.

The fact that 91% of the omnidirectional models, that is, isotropic models, suggests 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 (Lima et al., 2018).

Pests usually initiate colonization along the edges of the crop (Pedigo et al., 2021; Ramos et al., 2019). This pattern was observed in some pivots in the first three years. Differently, in the fourth year, the colonization started in the center of the crop.

The spatial distribution of pest insects in crops results from colonization and dispersal capacity (Martins et al., 2018; Pereira et al., 2019). Factors influencing the spatial distribution of these organisms in crops are the pest species characteristics, climatic elements, terrain relief, and surrounding vegetation (Ludwig et al., 2018; Martins et al., 2018; Pereira et al., 2019).

Wind also plays a key role in dispersing insects over short and long distances (Lima et al., 2018; Ludwig et al., 2018; Pereira et al., 2019). 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 (Bacca et al., 2006; Ramos et al., 2019; Souza et al., 1998). In addition, the wind also carries olfactory odors from host plants, in the case of *L. coffeella* from coffee trees (Pereira et al., 2007b; Pereira et al., 2019; Righi et al., 2013).

Surrounding vegetation can affect insect pest dispersion and colonization (Giffard et al., 2012; Nestel et al., 1994; Sciarretta and Trematerra, 2014; Sivakoff et al., 2013). 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 (Bacca et al., 2008; Felicio et al., 2019; Lima et al., 2018; Magalhães et al., 2008a; Magalhães et al., 2008b; Pereira et al., 2019; Teodoro et al., 2008). The rapid dispersion of adults of *L. coffeella* provides a gradual increase in 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 (Bongiovanni and Lowenberg-Deboer, 2004; Lima et al., 2018; Pereira et al., 2019).

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* (Meireles et al., 2001; Meireles et al., 2009).

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 891.58m to 4974.43m from each other, depending on the area size. Regarding isotropy, sampling should be done 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 it. 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.

Acknowledgments

We are grateful for the financial support provided by ‘Conselho Nacional de Desenvolvimento Científico e Tecnológico’, the ‘Coordenação de Aperfeiçoamento de Pessoal de Nível Superior’, Finance Code 001, and the ‘Fundação de Amparo a Pesquisa do Estado de Minas Gerais’ (FAPEMIG). Special thanks to Olam Coffee for providing financial support and data for this research.

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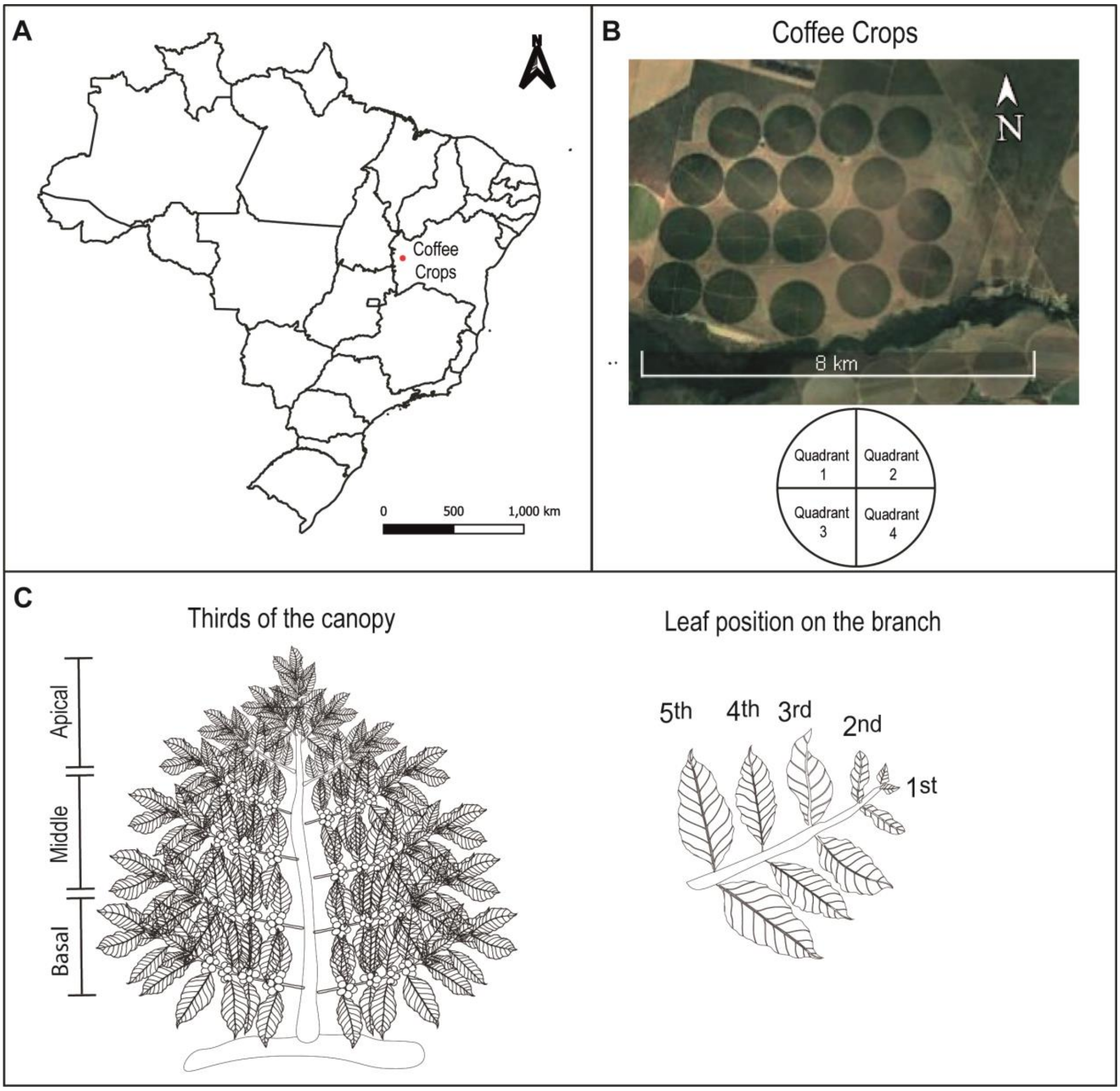

Figure 1 - Location of Coffee Crops and leaf position evaluated in sampling. (A) Milan Farm location in Brazil (B) pivot quadrants and (C) leaf position where the attack of *Leucoptera coffeella* was evaluated in the thirds of the canopy and in the branches.

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.

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

Pivots	Latitude	Longitude	Altitude (m)	Surrounding vegetation	Surrounding vegetation (%)			
					Norte	Leste	Sul	Oeste
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
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.

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

Date	Model	Anisotropy	Major range (A_0)	Minor range(A_0)	Direction (Degrees)	C0	C	Mean	RMSE	ME	RMSSE	ASE	RSD
4/1/2016	Spherical	No	1775.56	-	-	0.00081	0.0185	0.0027	0.0904	0.0186	0.9999	0.0917	0.0420
5/1/2016	Spherical	No	1086.17	-	-	0.00000	0.0136	0.0053	0.1016	0.0387	1.0043	0.0999	0.0000
6/1/2016	Spherical	No	1481.13	-	-	0.00000	0.0163	0.0023	0.0889	0.0190	0.9926	0.0903	0.0000
7/1/2016	Spherical	No	1449.60	-	-	0.00201	0.0125	0.0013	0.0903	0.0144	1.0097	0.0899	0.1390
8/1/2016	Spherical	No	1382.90	-	-	0.00000	0.0127	0.0020	0.0825	0.0182	0.9782	0.0830	0.0000
9/1/2016	Spherical	No	1246.14	-	-	0.00000	0.0098	0.0010	0.0768	0.0089	1.0032	0.0776	0.0000
10/1/2016	Spherical	Yes	4452.01	1701.36	56.43	0.00449	0.0302	0.0001	0.1097	0.0031	1.0010	0.1113	0.1295
11/1/2016	Spherical	Yes	2663.02	891.58	58.18	0.00032	0.0103	0.0001	0.0707	0.0008	0.9920	0.0709	0.0303
12/1/2016	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
2/1/2017	Spherical	No	2389.14	-	-	0.00203	0.0316	0.0013	0.1058	0.0099	1.0012	1.0012	0.0603
3/1/2017	Spherical	No	1254.05	-	-	0.00000	0.0169	0.0012	0.1016	0.0021	1.0031	1.0031	0.0000
4/1/2017	Exponential	No	1583.42	-	-	0.00000	0.0073	0.0016	0.0738	0.0186	1.0083	0.0727	0.0000
5/1/2017	Spherical	No	1414.89	-	-	0.00000	0.0034	0.0034	0.0430	0.0108	1.0004	0.0426	0.0000
6/1/2017	Gaussian	Yes	1152.18	891.58	18.98	0.00000	0.0033	0.0256	0.0410	0.0256	1.0041	0.0409	0.0010
7/1/2017	Exponential	Yes	2051.51	1035.43	136.76	0.00000	0.0038	0.0009	0.0558	0.0135	1.0258	0.0534	0.0000
8/1/2017	Spherical	No	4974.43	-	-	0.00000	0.0367	0.0006	0.0705	0.0042	0.9716	0.0721	0.0000
9/1/2017	Spherical	No	4554.92	-	-	0.00687	0.0366	0.0008	0.1204	0.0051	1.0395	0.1146	0.1582
10/1/2017	Circular	No	1565.12	-	-	0.00000	0.0436	0.0003	0.1193	0.0047	0.9477	0.1280	0.0000
11/1/2017	Exponential	No	935.10	-	-	0.00000	0.0092	0.0008	0.0936	0.0048	0.9973	0.0943	0.0000
12/1/2017	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
2/1/2018	Gaussian	No	1482.70	-	-	0.00059	0.0013	0.0001	0.0302	0.0056	1.0005	0.0305	0.3054
3/1/2018	Gaussian	No	1796.67	-	-	0.00119	0.0053	0.0000	0.0450	0.0047	1.0177	0.0458	0.1837
4/1/2018	Gaussian	No	2266.36	-	-	0.00153	0.0109	0.0005	0.0489	0.0054	1.0062	0.0499	0.1232
5/1/2018	Gaussian	No	1090.22	-	-	0.00012	0.1200	0.0007	0.0485	0.0251	1.0100	0.0514	0.0010
6/1/2018	Spherical	No	1219.08	-	-	0.00000	0.0697	0.0020	0.0446	0.0150	1.0012	0.0539	0.0000
7/1/2018	Gaussian	No	1323.05	-	-	0.00023	0.2273	0.0085	0.0774	0.0062	1.0269	0.0932	0.0010
8/1/2018	Gaussian	No	1035.68	-	-	0.00000	0.0036	0.0010	0.0401	0.0164	1.0015	0.0406	0.0010
9/1/2018	Spherical	No	1043.13	-	-	0.00025	0.0021	0.0015	0.0416	0.0349	1.0043	0.0413	0.1086
10/1/2018	Gaussian	No	891.58	-	-	0.00004	0.0019	0.0003	0.0358	0.0119	1.0080	0.0354	0.0202
11/1/2018	Spherical	No	1348.62	-	-	0.00000	0.0011	0.0005	0.0245	0.0219	1.0007	0.0246	0.0000

12/1/2018	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
2/1/2019	Spherical	No	2243.60	-	-	0.00000	0.0012	0.0000	0.0193	0.0007	1.0015	0.0193	0.0000
3/1/2019	Spherical	No	2248.93	-	-	0.00000	0.0032	0.0008	0.0317	0.0239	0.9981	0.0328	0.0000
4/1/2019	Gaussian	No	1094.75	-	-	0.00001	0.0057	0.0002	0.0433	0.0043	1.0015	0.0471	0.0010
5/1/2019	Exponential	No	1633.17	-	-	0.00000	0.0068	0.0022	0.0689	0.0270	1.0034	0.0689	0.0000
6/1/2019	Spherical	No	1280.81	-	-	0.00000	0.0105	0.0010	0.0785	0.0077	1.0042	0.0789	0.0000
7/1/2019	Spherical	No	996.88	-	-	0.00000	0.0045	0.0001	0.0595	0.0040	1.0011	0.0596	0.0000
8/1/2019	Gaussian	No	2146.96	-	-	0.00080	0.0045	0.0001	0.0353	0.0012	1.0000	0.0358	0.1517
9/1/2019	Spherical	No	1340.11	-	-	0.00000	0.0014	0.0001	0.0283	0.0032	0.9934	0.0288	0.0000
10/1/2019	Spherical	No	983.21	-	-	0.00000	0.0005	0.0004	0.0209	0.0199	1.0164	0.0206	0.0000
11/1/2019	Gaussian	No	1280.59	-	-	0.00000	0.0023	0.0008	0.0249	0.0297	1.0003	0.0246	0.0010
12/1/2019	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
2/1/2020	Spherical	No	891.58	-	-	0.00003	0.0001	0.0004	0.0114	0.0303	0.9973	0.0114	0.1685

Legend: A_0= range, C_0 = nugget effect, C = still, 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.

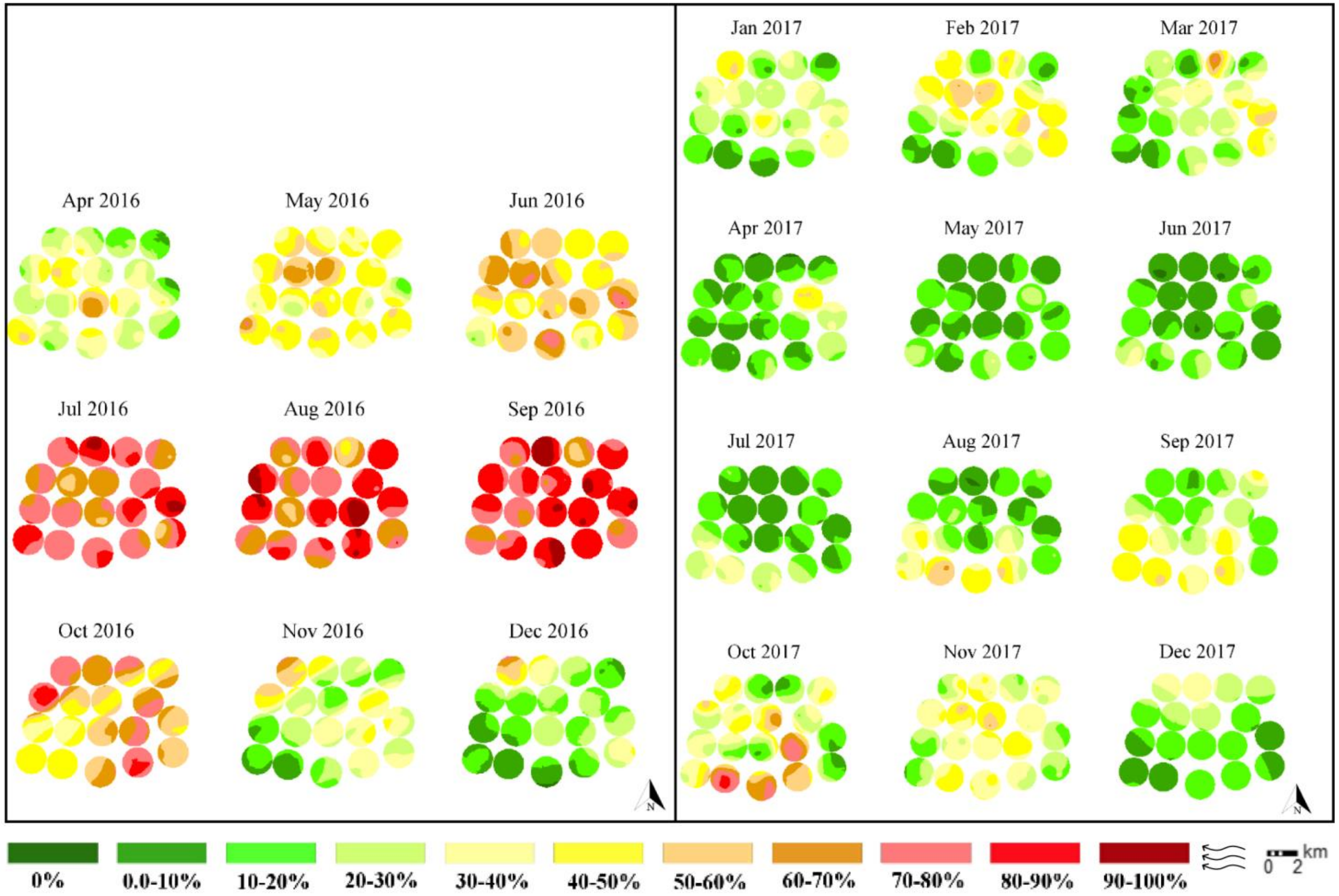

Figure 3 - Spatial distribution maps of *Leucoptera coffeella* in the 18 coffee cultivation pivots of Milan Farm from April to December 2016 (year 1) and from January to December 2017 (year 2). Each circle on the map represents a 100 ha pivot. The color indicates the percentage (in the bars) of *L. coffeella*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

CHAPTER 3: DECISION-MAKING SYSTEM FOR THE CONTROL OF *Leucoptera coffeella* IN COFFEE CROPS USING MANAGEMENT ZONES

ABSTRACT

Management zones are areas in the field with similar characteristics that respond to inputs uniformly. These management zones can be used in integrated pest management programs for pest control making-decision. Coffee is the second commodity globally, and the coffee leaf miner *Leucoptera coffeella* is one of its main pests in the key-producing regions of the world. Thus, the objective of this study was to propose a decision-making system to control *L. coffeella* in coffee crops using management zones. The study was performed for four years on 18 pivots of 100 ha of *Coffea arabica* in a total of 1800 ha. The programs studied were: CI - conventional with the monthly application; IPM-Md - application if density (D) in 1800 ha ≥ ET (control level = 30%); IPM-Pd - pivot application where D ≥ ET and IPM-Mz - two management zones: (1) D ≥ ET (pest control) and (2) D < ET (non-control). The IPM-MD, IPM-Pd, and IPM-Mz programs reduced insecticides and made better decisions. The IPM-Mz program was the best, followed by the IPM-Pd program. Therefore, the program using *L. coffeella* management zones can be incorporated into integrated pest management programs in coffee crops, as it enables pest control in places where it is necessary, reducing production costs and the environmental impact of insecticide use.

Keywords: *Coffea Arabica*. Coffee Leaf miner. Precision Agriculture. Integrated Pest Management. Cost reduction. Insecticide Use Reduction.

7. INTRODUCTION

Precision agriculture (PA) is a science that analyses temporal, spatial, and individual data. This information is used to guide site management decisions and optimize agricultural resources, improve the quality, reduce costs and increase profitability (Kolady et al., 2021; Singh et al., 2020).

In traditional agriculture, pest control can be performed using conventional systems. In the conventional system, periodic spraying of insecticides is carried out following a schedule of applications (Pedigo et al., 2021; Picanço et al., 2014). Conversely, precision agriculture uses modern equipment and techniques of the Integrated Pest Management Programs (IPM). In IPM, the pest management decision is based on sampling and economic injury levels. The control decision is only taken when the pest densities are equal to or greater than the economic injury level (Bacci et al., 2007; Bueno et al., 2017; Picanço et al., 2014; Williams et al., 2005).

In IPM programs, sampling can be carried out (i) by dividing the cultivation area into plots, (ii) without dividing the cultivation area into plots, or (iii) using management zones (Bacci et al., 2007; López et al., 2019; Sahu et al., 2019). In situations where sampling is performed by plot, each one must be uniform, having the same topography, soil type, cultivar, planting time, spacing, and crop management. The plot size can be variable, ranging from small areas with less than one hectare to large ones, reaching up to 100 hectares (Bacci et al., 2007).

In large areas and regions where farmers have an associative culture, pest and disease control decisions are often based on evaluating an area that serves as a representative parameter for all crops. This system is used in phytosanitary warning stations where climatic elements and pest and disease populations are monitored in a single area. Based on the data obtained in this area, phytosanitary warning bulletins are published to guide the decision to control or not a particular pest or disease (López et al., 2019; Noar et al., 2021; Picanço M.C. et al., 2016).

Management zones are crop areas with similar characteristics for one or more variables. In each of the management zones, inputs must be applied uniformly. In IPM programs, management zones represent crop areas with similar pest densities. Thus, based on precision agriculture principles, the control decision in each of these management zones must be made individually, respecting their particularities (El-Ghany et al., 2020; Méndez-Vázquez et al., 2019).

Coffee is the second commodity worldwide, only behind petroleum oil (Avelino et al., 2018). Its production and world trade move 102.02 billion dollars annually (Intelligence, 2021). In addition, coffee is the second most consumed beverage globally (Hu et al., 2020). Coffee is mainly grown in the Americas (56.97% of world production), Asia (30.58%), and Africa (12.06%). Brazil is the largest producer of all countries, accounting for 44.62% of world production in the last harvest (FAOSTAT, 2021). However, insect pests are one of the main factors causing losses in coffee fields (Hu et al., 2020; Leite et al., 2020b; Rosado et al., 2021).

The coffee leaf miner *Leucoptera coffeella* (Guérin-Méneville) (Lepidoptera: Lyonetiidae) is the main insect pests attacking coffee plants (Dantas et al., 2021; Pantoja-Gomez et al., 2019). This pest is distributed in the South and Central America, in some countries on the African continent, and Saudi Arabia and Sri Lankaa in Asia (Dantas et al., 2021; Leite et al., 2020b; Pantoja-Gomez et al., 2019; Tuelher et al., 2003) This microlepidopteran feeds on the leaf parenchyma in the immature phase, causing damage to the leaves. Consequently, there is a reduction in leaf area, early senescence of the leaves, and reduction of the plant's photosynthetic capacity (Souza et al., 1998). At high densities, *L. coffeella* can reduce the productivity of coffee crops by up to 87% (Dantas et al., 2021; Leite et al., 2021; Motta et al., 2021; Ramiro et al., 2004).

Despite the damage caused by *L. coffeella* in coffee crops, most of the research efforts on this pest manage are focused on the control measures such as chemical control, biological control, insecticides resistance management, and spray technology (Leite et al., 2020a; Leite et al., 2021; Melo et al., 2019; Rezende et al., 2014; Rosado et al., 2021). When it comes to decision-making processes, there is no study on the use of management zones to manage *L. coffeella*. Thus, this research aimed to propose a decision-making system to control *L. coffeella* in coffee crops using different programs, including management zones.

8. MATERIAL AND METHODS

2.1 Study area

This study was undertaken in Arabica coffee crops, red catuaí variety, Milan Farm in Barreiras, Bahia, Brazil (45°30'29.44" W, 12°18'16.04" S) during four years (April 2016 to February 2020). The evaluated areas were located in the Cerrado biome and represent the locations with the highest attack intensities of *L. coffeella* in Brazil (Leite et al., 2020a; Leite et al., 2020b; Leite et al., 2021). Milan Farm has 18 central pivots of 100 hectares each, with a total area of 1,800 hectares. In coffee crops, the spacing was 3 x 1 m and center pivot irrigation. The whole area was evaluated in this study. Milan farm uses the application of insecticides Abamectin, Thiamethoxam, Chlorantraniliprole, and Novalurom to control *L. coffeella*.

2.2 Data Sampling

Arabica coffee plants were divided into three strata: apical, median, and basal for sampling. Leaves from the middle and the apical stratum were used in the assessments because they correlated with the total densities of the pest (Reis and Souza, 1996). The density of *L. coffeella* was determined by counting the number of leaves with active mines (i.e., containing alive larvae). To quantify the percentage (%) of *L. coffeella* density, the equation (1) was used:

$$\%\, L.coffeella\ infestation = \left(\frac{number\ of\ leaves\ with\ live\ larvae}{total\ number\ of\ sampled\ leaves}\right) * 100 \qquad (1)$$

Pest densities were evaluated monthly from April 2016 to February 2020, totaling four pest assessments. Four leaves per plant were collected in 25 plants per quadrant, totaling 100 plants for each pivot. Subsequently, the average of the 25 samples from each quadrant was calculated, and the georeferencing data were collected in the center of the quadrant.

2.3 Pest control programs

Simulations concerning the *L. coffeella* control were performed using four management programs. The first program was the conventional control (Cl). In this program, the monthly insecticide application was carried out throughout the area. Coffee growers frequently use this management program in the Brazilian Cerrado to control this pest (Leite et al., 2020b; Leite et al., 2021). The second program was insecticide application in the whole area when the average pest density in the area was equal to or greater than the control level (30% of active mined leaves), which we called IPM-Md. The third program was the insecticide application only on the pivot where the pest density was equal to or greater than the control level (IPM-Pd). The fourth program was insecticide application according to the management zone (IPM-Mz), insecticide application only in the pivot area where the pest density reached the control level. Figure 1 explains the four management programs.

Semivariograms were estimated from the data of pest densities in each month of cultivation (Ramos et al., 2019). Subsequently, interpolation was performed to estimate the pest densities in the area by the kriging method. The management zone maps of *L. coffeella* densities in each pivot and month of pest evaluation were built using the software ArcGIS version 10.0 (ESRI, 2016). Two pest management zones were established on the maps. In the first, the density of *L. coffeella* was lower than the control level, and there was no need to perform any pest control. In the second, the insect density was equal to or greater than the control level; therefore, the pesticide application was needed. The size (ha) of the areas of each of the two management zones at each pivot and assessment date was calculated using the software ArcGIS version 10.0 (ESRI, 2016).

The size of the areas (in hectares) of pest control was estimated for each month, coffee cultivation pivot, and control program. Histograms were made of the areas size (in hectares) of pest control (monthly and total during the 47 months) for each control program (CI, IPM-Md, IPM-Pd, and IPM-Mz).

Then, errors in control and non-control decisions were calculated. To calculate these errors in the CI, IMP-Pd, and IPM-Md programs, we use the management zones program (IMP-Mz) as a standard, allowing us to identify the areas that need the control application precisely. In this way, we calculate the size of the area (ha) in which the control decision was wrong in each program.

When the control or non-control decisions in CI, IPM-Md, and IPM-Pd programs differed from management zones (IPM-Mz), they were considered wrong.

Subsequently, it was built histograms of the estimates (monthly and total) of the areas where errors occurred in the control decision in the CI, IPM-Md, and IPM-Pd programs.

3. RESULTS

Figure 2 shows the spatial distribution maps of *L. coffeella* in the 18 coffee cultivation pivots during the four years of this research. The area size (ha) where the pest density population must be controlled varies according to the control program adopted (Figure 3A).

During the 47 months of the evaluations, the control programs for *L. coffeella* using control level (30% of active mined leaves) reduced the need for insecticide use by about 70%, concerning the monthly applications of these products. The areas treated with insecticides in the three programs were similar (Figure 3B). Despite the similar size of these three areas, they belonged to different locations, and therefore insecticide applications should be carried out at different times (Figure 3A).

The control program with insecticide application in the pivot areas where the density of *L. coffeella* reached the control level was adopted as a standard because the control is only performed in places where the pest could cause economic damage. The size of the areas where the control decision was not correct varied among the control programs (Figure 4A). According to our analyses, chemical control was unnecessary in 70.74% of the area with monthly applications.

In the insecticide application program throughout the area (IPM-Md), when the average density of the pest reached the control level, errors occurred in the decision of control in 13.02% of the situations, being 5.71% of these errors due to control decisions, and 7.31% were due to non-control decisions. In the insecticide application program (IPM-Pd), only in the pivot where the pest density reached the control level, the errors were 1.47% of the situations, with 1.11% of these errors due to control decisions and 0.36% were due to non-control decisions (Figure 4B).

4. DISCUSSION

Chemical control is the main method used in coffee crops to reduce the population density of *L. coffeella* (Fragoso et al., 2002; Leite et al., 2020b). This method is used due to its efficiency, speed of action, residual period of control, and cost/benefit ratio (Dantas et al., 2021; Guastella et al., 2017; Leite et al., 2020b; Leite et al., 2021). The control efficiency of *L. coffeella* is related to the efficiency of insecticides used, frequency of application, migration, dispersion of the species in the field, and the selection of populations resistant to insecticides (Costa et al., 2016; Dantas et al., 2021; Fragoso et al., 2003; Leite et al., 2020b).

In favorable regions to *L. coffeella*, such as coffee crops in the Cerrado, the attack intensities of this pest are high (Leite et al., 2020b; Leite et al., 2021). In these situations, the cost of controlling *L. coffeella* is high due to the acquisition of insecticides, the number of applications carried out, and the use of machines, equipment, and labor in the applications (Guerreiro Filho, 2006). The results obtained in this study demonstrate the advantages of using management zones in the integrated pest management program to control *L. coffeella* in coffee fields. In this context, adopting these principles makes it possible to reduce the number of applications, the costs of pest control, and the environmental impact caused by these products (Guastella et al., 2017; Leite et al., 2020b).

The monthly insecticide application (CI) program is the most used by coffee growers to control *L. coffeella* in their fields. This program uses insecticides from different chemical groups (Costa et al., 2016; Leite et al., 2021). Currently, 152 commercial products belonging to 42 active ingredients and 16 chemical groups are registered in Brazil to *L. coffeella* control in coffee (MAPA, 2022). Using this strategy, the continuous use of insecticides favors the selection of pest populations resistant to pesticides (Dantas et al., 2021; Fragoso et al., 2003; Fragoso et al., 2002; Leite et al., 2020a). It has already been reported that populations of *L. coffeella* showed insecticide resistance to the organophosphates disulfoton, ethion, methyl parathion, and chlorpyrifos, the neonicotinoid thiamethoxam and the diamide chlorantraniliprole (Costa et al., 2016; Fragoso et al., 2003; Fragoso et al., 2002; Leite et al., 2020a; Leite et al., 2021). In addition, the lack of pest sampling does not allow the coffee grower to verify the efficiency of the control method employed (Leite et al., 2020b).

The monthly application of insecticides to control *L. coffeella* increased the need to apply insecticides by 70%. This unnecessary use of pesticides increases the cost of coffee production. In addition, excessive use of insecticides can negatively impact the populations of natural enemies and pollinators (Bueno et al., 2017; Medeiros et al., 2019; Melo et al., 2019). This negative impact occurs due to mortality and effects on development and reproduction. Also, biological pest control and plant pollination are affected as well. (Carvalho G.A. et al., 2019; Park et al., 2015; Stefanello Júnior et al., 2008).

The three programs (IPM-Md, IPM-Pd, and IPM-Mz) that used the IPM principles reduced the use of insecticides and made better decisions in the control of *L. coffeella*. Among these three programs, the one with control decision-making using management zones (IPM-Mz) was the best, followed by the program with the division of areas into stands (the pivots) (IPM-Pd). These positive results were due to two pillars of integrated pest management: sampling and indices for decision-making (e.g., control level) (Fernandes et al., 2011; Leite et al., 2020b; Pedigo et al., 1986).

The program with the use of management zones was the one that allowed greater savings, located decisions, and minimization of the use of insecticides due to the control being recommended only in areas where the pest could cause economic damage. In this management strategy, it is necessary to collect georeferenced samples in the field with GPS (Huuskonen and Oksanen, 2018; Oliver, 2010), a computerized system and precision agriculture software that establishes management zones (Paccioretti et al., 2020), and appropriate application equipment (for example robot platforms and unmanned aerial vehicle) (Jha et al., 2019; Meshram et al., 2022). These requirements represent a higher fixed cost (Ahmad and Mahdi, 2018; Langemeier and Shockley, 2019) which are compatible with large producers and with medium and small producers associated with cooperatives.

Equipment used in insecticide applications on management zone programs must have remote communication systems. These systems use a data processing center, artificial intelligence, and georeferencing to identify the areas that need control and precise application of the products (Bacci et al., 2007; Ramos et al., 2019). This decision-making system can also be used in the application of natural products (Shanmugam et al., 2015), entomopathogens (Preininger et al., 2018), and semiochemicals (Castrignanò et al., 2020).

Small coffee growers who do not have enough resources to invest in precision agriculture equipment are recommended to use the strategy of dividing areas into plots (IPM-Pd). This program had the second-best performance in reducing production cost, insecticides use, and success in control decisions *L. coffeella* in coffee crops. With this program, the small farmer can make adaptations and use the principles of the management zones, carrying out the application of control only in the coffee crops areas where there are *L. coffeella* outbreaks in which the pest density is equal to or greater than the control level (Bacci et al., 2007; Ramos et al., 2019).

The integrated management programs showed in this study reduce the insecticide applications. The control or non-control error decisions in these programs were low compared to the conventional program. Management zones' decision-making can be incorporated into integrated pest management programs in coffee crops since it greatly reduces (70%) the need to use insecticides to control *L. coffeella*. Furthermore, this system makes it possible to reduce the costs of controlling other pests and diseases, fertilization, and crop management in general. In addition to reducing the negative environmental impact of the control methods used.

Acknowledgments

We are grateful for the financial support provided by ‘Conselho Nacional de Desenvolvimento Científico e Tecnológico’, the ‘Coordenação de Aperfeiçoamento de Pessoal de Nível Superior’, Finance Code 001, and the ‘Fundação de Amparo à Pesquisa do Estado de Minas Gerais’ (FAPEMIG). Special thanks to Olam Coffee for providing financial support and data.

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CI monthly insecticide application	IPM-Md insecticide application in the whole area when the average pest density reached the control level (ET = 30% of mined leaves)
IPM-Pd insecticide application only in the pivot where the pest density reached the ET	IPM-Mz insecticide application only in the pivot area where the pest density reached the ET (this area was defined in the maps of spatial distributions of the insect

Figure 1 - The four types of management programs for *L. coffeella* in coffee crops. The first (top left) CI program: monthly applied insecticide throughout the area. The second (upper right) IPM-Md program: applied insecticide throughout the area when the average density of the pest in the area was equal to or greater than the control level (30% of mined active leaves). The third (bottom left) IPM-Pd program: applied insecticide only to the pivot where the pest density was equal to or greater than the control level (30% of mined active leaves). The fourth (bottom right) IPM-Mz program: applied insecticide only in the pivot area where the pest density reached the control level (30% of mined active leaves).

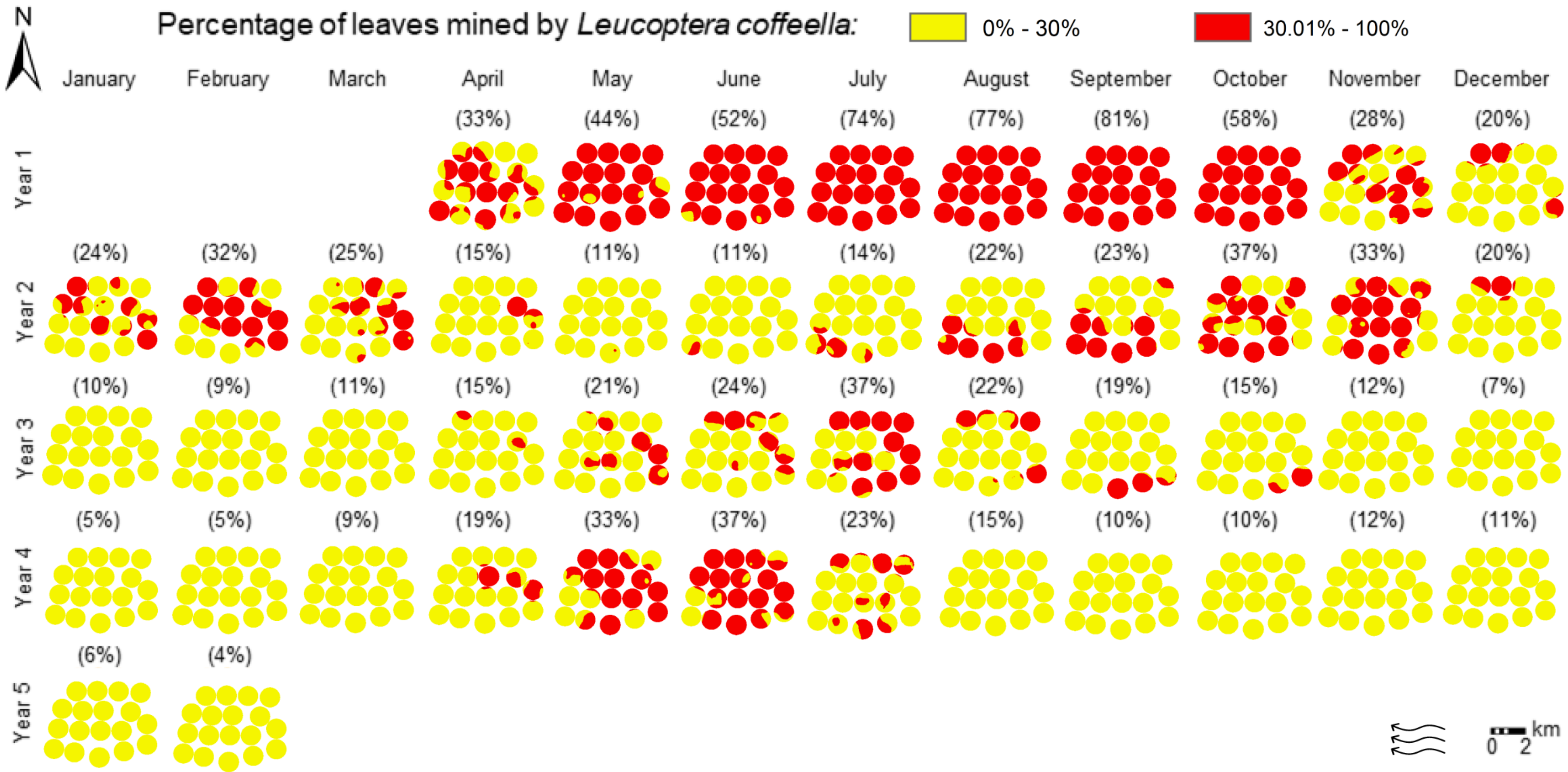

Figure 2 - Spatial maps distribution of *Leucoptera coffeella* in the 18 pivots from April 2016 (year 1) to February 2020 (year 5). Each circle on the map represents a 100 ha pivot, and the numbers (percentage) in parentheses correspond to *L. coffeella* density.

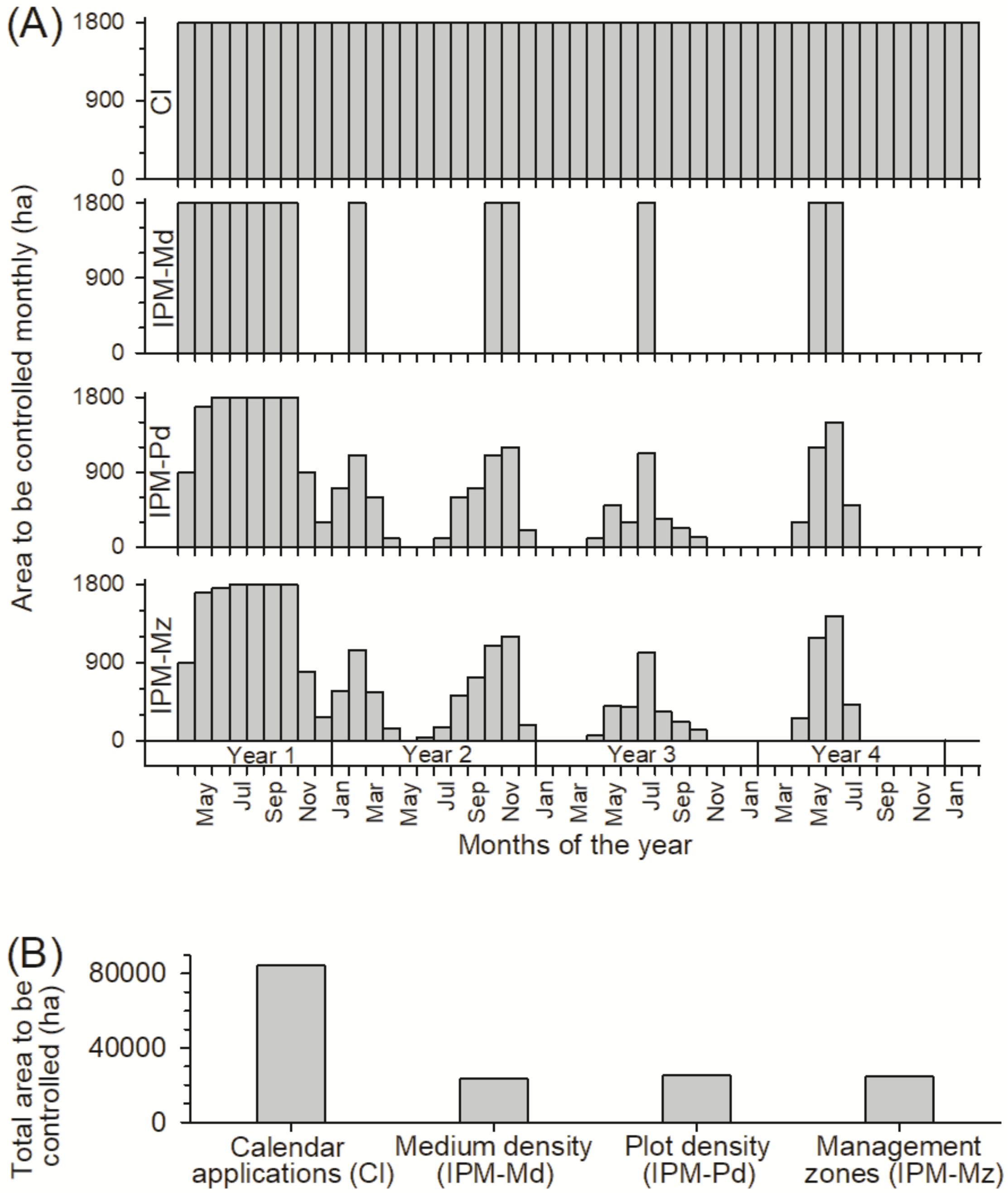

Figure 3 - *Leucoptera coffeella* control areas in four programs: CI = monthly insecticide application, IPM-Md = insecticide application in the whole area when the average pest density reached the control level (ET = 30% of active mined leaves), IPM-Pd = insecticide application only in the pivot where the pest density reached the ET, and IPM-Mz = insecticide application only in the pivot area where the pest density reached the ET (this area was defined in the maps of spatial distributions of the insect). (A) Monthly variation of pest control areas and (B) total pest control area.

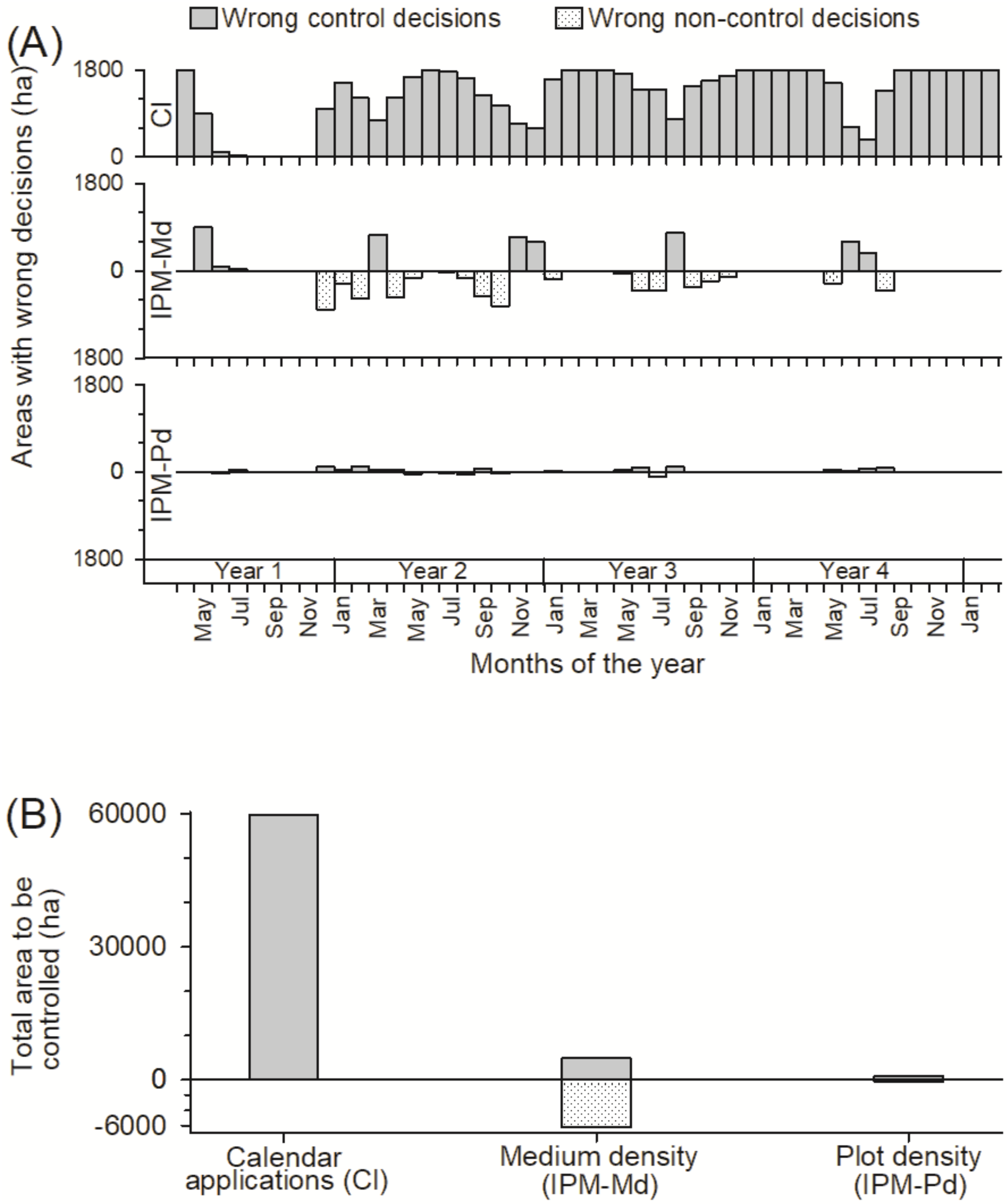

Figure 4 - Areas of coffee crops with errors in the decision to control *Leucoptera coffeella* in three programs: CI = monthly insecticide application, IPM-Md = insecticide application in the whole area when the average pest density reached the action level (ET = 30% of active mined leaves), and IPM-Pd = insecticide application only on the pivot where the pest density reached ET. (A) Monthly variation of areas with errors in the control decision and (B) total area with errors in the control decision. The management zones (IPM-Mz) defined in the spatial distribution maps of the pest were used as a decision-making standard; therefore, they are not in the graphs.

GENERAL CONCLUSIONS

The population dynamics of *L. coffeella* are influenced by climatic elements in the studied biomes. Although *L. coffeella* is a worldwide important pest for coffee production, in Atlantic Forest plantations, *L. coffeella* did not reach control levels during all years studied. On the other hand, coffee crops cultivated in the Cerrado biome have higher population densities of *L. coffeella*, often reaching and exceeding the level of economic damage. This is attributed to climatic factors favorable to the development of the pest, planting the coffee crop in full sun, and the way in which cultivation is conducted (irrigated crops).

Additionally, during the months of July and October, the population density exceeds the EIL; therefore, pest management must be carefully elaborated. Due to these differences between the population densities of *L. coffeella* in the two biomes, crops located in the Cerrado need to be evaluated more frequently than crops in the Atlantic Forest.

Colonization of *L. coffeella* generally follows a pattern starting at the edge of the crop. The vegetation around the pivots of the farm studied here did not influence the pest dispersion in the field. Our study reports a high aggregation pattern and a high spatial dependence interval for *L. coffeella* in the studied area. Sampling should be performed equidistantly, as the pest is distributed equally in all directions in the field.

From the point of view of integrated pest management, during the periods of highest pest incidence, from July to October, sampling should be carried out frequently at the edges of the pivots, as most of the infestation starts there.

Regarding the decision-making system programs proposed in this work, implementing the two programs ─ the one that divides the area in plots and the one that uses the management zones ─ reduces the use of insecticides by 70% compared to the application by the calendar. Furthermore, control errors are very low, less than 2%, indicating these two programs' efficiency in controlling *L. coffeella*.

Hence, our research provides guidance for an effective integrated pest management program for *L. coffeella*. The usage of periodic sampling intensified during the pest’s outbreaks seasons, and the control levels in the decision-making process and the pest distribution allow the adoption of efficient control measurements to reduce *L. coffeella* densities before it reaches the economic injury level.