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Original Article

Spatiotemporal distribution of *Schizaphis graminum* (Rondani) and its natural enemy *Coccinella septempunctata* (Linnaeus) in graniferous sorghum crops

Distribuição espaço-temporal de *Schizaphis graminum* e seu inimigo natural *Coccinela septempunctata* em lavoura de sorgo granífero

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Abstract
At the global level, Sorghum bicolor (L.), is one of the most important crops, which ranks fifth among all cereals. It is cultivated in Africa, Asia, Oceania and the Americas, where it serves as a source of food and feed for humans and animals, respectively. However, production is constrained by several factors including pests and diseases. Among the pests that are known to attack Sorghum, Schizaphis graminum (Rondani), commonly called the green cereal aphid, is the most destructive pest of sorghum. S. graminum damage to sorghum is worsen by water deficit which favors its occurrence. Limited information on the spatial distribution of the pest and its natural enemies impedes the development of ecologically friendly management strategies. Therefore, the objective of this research was to determine the spatiotemporal distribution of S. graminum and its natural enemy Coccinella septempunctata (L.) during the vegetative and reproductive stage of the crop using geostatistical analysis. The spatiotemporal distribution of S. graminum was influenced by Sorghum development stage, surrounding landscape, and presence of its main predator C. septempunctata. Moreover, the abundance of C. septempunctata was influenced by the density of S. graminum. The findings from this study are required for developing sustainable pest management strategies against S. graminum.

Keywords: aphids, biological control, geostatistic, pest management, *Sorghum bicolor*.

Resumo
Em uma escala global o Sorghum bicolor (L.) é uma das culturas mais importantes, ocupando o quinto lugar entre todos os cereais. É cultivada na África, Ásia, Oceania e Américas, onde serve como fonte de alimento e ração para humanos e animais, respectivamente. No entanto, a produção é limitada por vários fatores, incluindo pragas e doenças. Entre as pragas que atacam o sorgo, *Schizaphis graminum* (Rondani), comumente chamado de pulgão verde dos cereais, é a praga mais destrutiva do sorgo. O dano de *S. graminum* ao sorgo é agravado pelo déficit hídrico que favorece sua ocorrência. Informações limitadas sobre a distribuição espacial da praga e seus inimigos naturais impedem o desenvolvimento de estratégias de manejo ecologicamente corretas. Portanto, o objetivo desta pesquisa foi determinar a distribuição espaço-temporal de *S. graminum* e seu inimigo natural *Coccinella septempunctata* (L.) durante a fase vegetativa e reprodutiva da cultura por meio de análise geoestatística. A distribuição espaço-temporal de *S. graminum* foi influenciada pelo estágio de desenvolvimento do sorgo, paisagem circundante e presença de seu principal predador *C. septempunctata*. Além disso, a abundância de *C. septempunctata* foi influenciada pela densidade de *S. graminum*. Os resultados deste estudo são necessários para o desenvolvimento de estratégias sustentáveis de manejo de pragas contra *S. graminum*.

Palavras-chave: afídeos, controle biológico, geoestatística, manejo de pragas, *Sorghum bicolor*.

1. Introduction

Sorghum bicolor (L.) Moench, is a cereal crop native to Africa. In the Asian and African continent and other regions, it serves as a potential source of nutrition for human consumption (Espitia-Hernández et al., 2022;

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Thilakarathna et al., 2022). Outside its aboriginal home, it is found in all the continents except for Antarctica. The expansion of geographical distribution of the crop has been associated with its drought tolerance and adaptation to temperate climates (Borghi et al., 2016). In Asia, Africa and other semi-arid regions, it serves as a source of food, and has been useful in the alcoholic beverage industries. However, in the United States, Australia, and Brazil, it is used to produce animal feed and fodder. There are four types of sorghum namely; saccharine, broom, forage, and grain. Saccharin, which has sweet and succulent culm is used in the production of forage and ethanol, while the broom type is used for the production of brooms and animal feed. Forage type is used for animal feed, whereas the grain is consumed as food and feed for humans and animals, respectively (May et al., 2013).

Sorghum is associated with a wide variety of arthropod pests, such as *Conoderus scalaris* (Germar), the caterpillar elasmus *Elasmopalpus lignosellus* (Zeller), the caterpillar of the corn cartridge *Spodoptera frugiperda* (J.E. Smith), sorghum fly *Stenodiplosis sorghicola* (Coquillett), corn aphid *Rhopalosiphum maidis* (Fitch) and green aphid *S. graminum* (Waquil et al., 2003; Nboyine et al., 2021; Okosun et al., 2021).

Currently, the green cereal aphid (*Schizaphis graminum*) is the economically important pest of sorghum. It inflicts severe damage to the crop, and this has been exacerbated by water deficit that favors its occurrence. The aphid sucks sap and inject toxins into the host, which leads to tanned tissue with wrinkled leaves and subsequent plant's death if not properly managed (Karban and Myers, 1989; Zhang et al., 2019). The feeding activities release sugary excrement called "honeydew", which makes the leaves sticky, thereby exposing it secondary infection by fungi. The symptomatic leaves show dark layer on the leaf known as sooty mold (*Capnodium* sp.), which prevents the exchange of gases, thereby restricting the photosynthetic activities of the plant (Insausti et al., 2015). In addition, the green aphid is a vector of disease-causing viruses such as the sugarcane mosaic (Gallo et al., 2002).

Among the pest control alternatives, biological control appears as a natural phenomenon that efficiently regulates the population of pests. The abundance of a pest increases with availability of food and favorable climatic conditions (Menezes, 2003). With the increase in pest abundance, there is a spontaneous increase in the density of natural enemies, causing a drop in the pest population. Given the new scenario of Integrated Pest Management (IPM), biological control is an essential alternative to chemical control which does not pose a threat to environmental and human health (Parra et al., 2002).

Within the IPM, predators are highly effective in biological control (Menezes, 2003). These are insects that feed on other insects, chewing them or sucking the contents of their body. Most predators are polyphagous (Silva and Brito, 2015). They are more effective in controlling where the population is dense or concentrated because immature predators do not move like adults, such as flying (Parra et al., 2002).

Ladybugs (Coccinellidae) are natural predators of several pests. They feed on aphids, white flies, scale insects, thrips, defoliating caterpillars in the early stages, and other arthropods, such as mites. Aphids also feed on fungi, nectar, and pollen (Silva, 2013). Previous studies which employed *Coccinella septempunctata* in their biological control programs showed positive results, however little is known about the species found in Brazil, necessitating for a behavioral and identification studies (Guerreiro, 2004).

In Brazil, ladybugs are not sold commercially but are used naturally in biological control, and the population occurs naturally in the agroecosystem. Therefore, agronomic practices must be carried out to conserve the natural enemies, prioritizing the use of selective chemical products in the IPM (Mendes et al., 2012).

In farming, biotic farming, biotic factors (e.g., natural enemies) and abiotic factors (e.g., rain and temperature) play an important role in determining the spatiotemporal distribution of pests (Waquil et al., 2003). Information on the spatial distribution of pests in the sorghum field can help determine the most frequent attack sites and their spread, making it a valuable strategy for IPM. Among the tools available to determine the spatial distribution of insects, geostatistics is an excellent alternative to investigate the spatial distribution of pests and predict their propagation during cultivation.

Therefore, the objective of this research was to determine the spatiotemporal distribution of *S. graminum* and its natural enemy *C. septempunctata* in a sorghum field during its vegetative and reproductive stage using geostatistical analysis.

2. Material and Methods

2.1. Characteristics of the experimental area

The experiment was carried out in the Rio Manso Experimental Farm, of the Federal University of Vales do Jequitinhonha and Mucuri (UFVJM), located in Couto de Magalhães de Minas municipality, Minas Gerais state, Brazil (Latitude 18°04'42"S, Longitude 43°27' 40"W). Data were collected between January and February 2020. The local is classified as Aw climate: tropical savanna (with dry winters and rainy summers), according to Köppen climate classification (Alvares et al., 2013).

The experimental area had a flat relief of approximately 4.02 hectares. Near it there were fragments of native savanna forest located to the northeast and west. On the southern border of the experimental area, there was a pasture with brachiaria grass and a rural road, which is part of the territory of the Rio Manso Experimental Farm of the UFVJM (Figure 1).

2.2. Area preparation and sorghum planting

Conventional soil preparation was carried out for the experiment The brachiaria grass existing at the site was incorporated with a disc plough. Afterwards, a fertilizer of 2,140kg/ha of PRNT 80% dolomitic limestone was applied in a haul, with the Lancer limestone spreader incorporated at 20 cm with the aid of a heavy plough harrow. Before planting, the area was homogenized using a leveling grid.

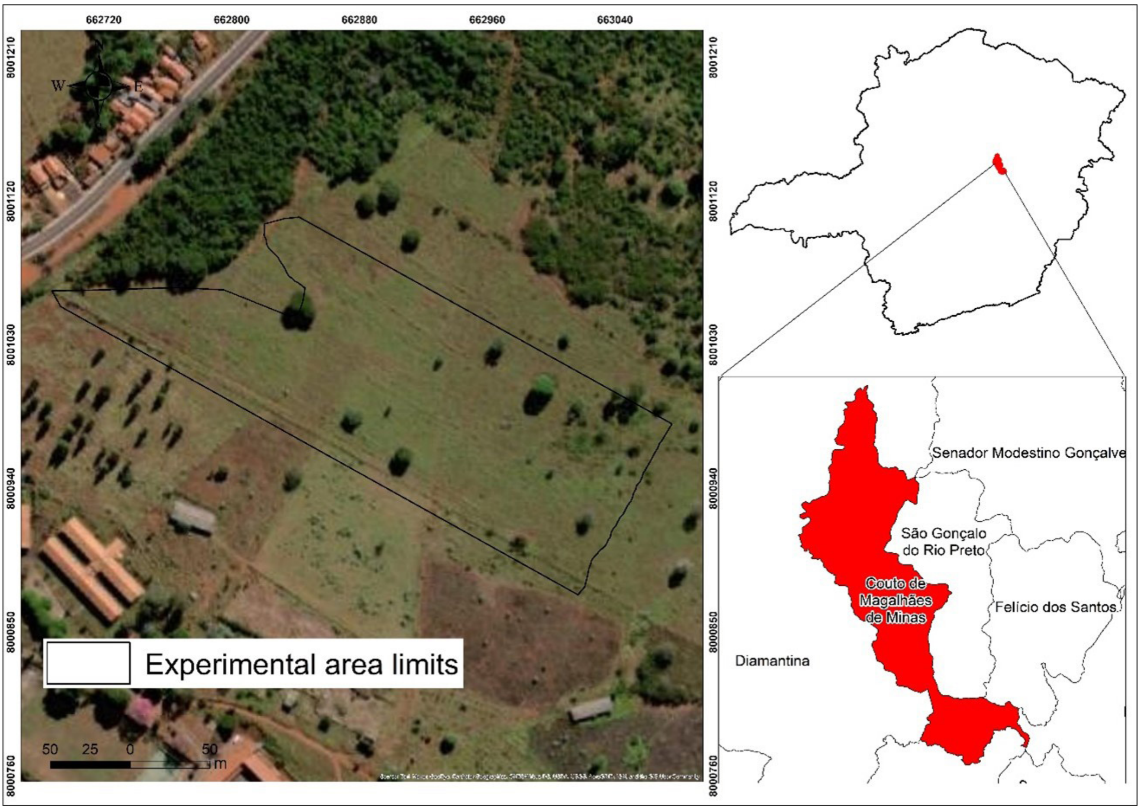

Figure 1. Map of the experimental area.

The planting of sorghum was carried out on 19th and 20th of November, 2019, in a mechanized manner using the 4-line Jumil Fertilizer Planter. The seeds were of the SHS 2010 genotype. Fertilization was carried out by planting in furrows, using 70kg/ha of P2O5, with triple superphosphate as a source. On 7th January, 2020, the top-dressing fertilization was carried out with the Adubadora-Distribuidora Soft by applying 100kg/ha of N as source the pearlescent urea.

2.3. Data collection and statistical analysis

The experimental area was demarcated with a total of 89 georeferenced and equidistant points in 20 m. At each collect point, data on the occurrence of insects of the central and surrounding plants (north, south, east and west) were collected. So, there were five plants per evaluated point, totaling 445 plants in the experimental area. Direct counting of insects was performed for each plant, and this collection was carried out during the sorghum vegetative and reproductive stages.

The counting of both insects was performed through images taken of the central and surrounding plants at the 89 georeferenced points analyzed. We used a camera with 13 MP and a maximum resolution of 4128 x 3096 pixels. The images were enlarged using the PAINT application until it was possible to identify the aphids and thus carry out the direct count.

An exploratory occurrence data analysis of *S. graminum* and its natural enemy *C. septempunctata* was carried out during the sorghum vegetative and reproductive stages, to obtain the mean and standard deviation of the both insect's occurrence. Subsequently, this occurrence data was submitted to analysis of variance (ANOVA) and the means compared by Tukey test at 5% probability. In the SigmaPlot program, Pearson's correlation analysis between *S. graminum* and *C. septempunctata* was performed to identify the relationship between the data.

Finally, the data for *S. graminum* and *C. septempunctata* were also submitted to geostatistical analysis, in the GS+ software (Robertson, 2008), using the semivariogram. Theoretical models with the best fits for the semivariogram were selected (Felício, 2018). For each model, the existence of anisotropy in the 0°, 45°, 90°, and 135° directions was tested.

The level of spatial dependence (LSD) was determined using the following formula: $LSD = C_0/(C_0 + C)$, where C_0 = the nugget effect and $C + C_0$ = the sill. The spatial dependence of the semivariogram is considered strong when $LSD \leq 0.25$, moderate when $0.25 < LSD < 0.75$ and weak when $LSD > 0.75$ (Cambardella et al., 1994).

After choosing the models, ordinary kriging was performed to infer the data at the non-sampled locations to build spatial distribution maps (Isaaks and Srivastava, 1989).

During the experiment, precipitation was also collected since it could interfere the insects occurrence.

3. Results

The mean number of individuals of *S. graminum* differed between the vegetative and reproductive stages ($F1.176 = 5.72$, $P = 0.018$). It is higher in the vegetative stage (129 aphids per plant) and lower in the reproductive stage (89 aphids per plant) (Figure 2). On the other hand, the average population of its natural enemy, *C. septempunctata*, had a slight increase in the reproductive stage, although statistically not significant by the Tukey test at 5% probability ($F_{1,176}=0.38$, $P=0.54$) (Figure 2).

Figure 3 shows data on the distribution of the volume of rainfall in the experimental farm during the period of evaluations in January 2020. During this period, it rained a total of 330 mm. Of this total, 7 mm was accumulated seven days before the evaluation in the vegetative period. In contrast, a total of 260 mm was accumulated between the vegetative stage evaluations until the reproductive stage evaluation. There was a positive correlation between species in the reproductive stage ($r = 0.30$, $n = 89$, $P < 0.01$), but there was not in the vegetative stage ($r = 0.004$, $n = 89$, $P = 0.97$).

Table 1 shows semivariogram results, the nugget effect (C0), corresponds to the semivariance value for the Zero distance, indicating the variation or errors in obtaining the data. The threshold (C+C0) represents a semivariogram value close to the range. At this point, there is no longer spatial dependence between the samples. The range (Ao) indicates the distance where the semivariogram reaches the plateau, pointing to the limit where the samples are related to each other (Vieira, 2000).

The results of the geostatistical analysis show that the exponential model was the best fit to the data, with the highest coefficient of determination (R2) and the smallest sum of squares of residuals (RSS) (Table 1). The data showed isotropy, thus the spatial dependence was equal in all directions. Furthermore, there was strong spatial dependence for *S. graminum* in both stages evaluated. In contrast, for *C. septempunctata* the dependence was strong in the vegetative stage and moderate in the reproductive stage (Table 1).

The distribution of *S. graminum* in sorghum's vegetative and reproductive stages are illustrated in Figures 4-5, respectively. In the vegetative stage, the highest population incidence occurred in the central region of the crop, north-south direction. There was a slight reduction in the maximum population in the reproductive stage, and infestation patches remained on the borders, with higher concentrations in the southern and southwestern regions of the area.

There was a reduction in the central region of the crop of aphid incidence in the reproductive stage. In both stages

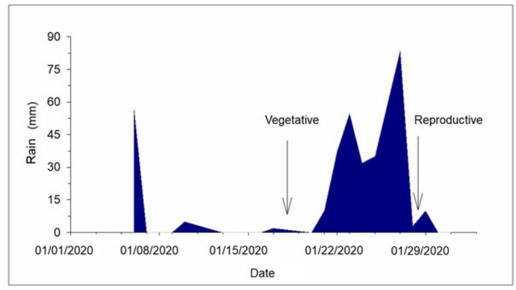

Figure 2. Number of individuals (mean ± standard error) per plant of the pest S. graminum (A) and the natural enemy C. septempunctata (B) in sorghum crop at the vegetative and reproductive development stages, respectively. The Tukey test's mean values followed by the same letters do not differ ($p < 0.05$).

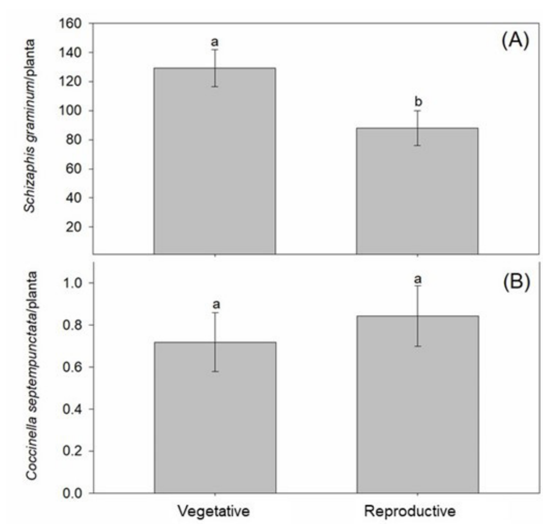

Figure 3. Rainfall distribution (mm) during the evaluation period. The arrows indicate the timing of evaluations in the vegetative and reproductive stages.

Table 1. Characteristics of the spatial distribution patterns of *S. graminum* and its natural enemy *C. septempunctata* in the sorghum vegetative (V) and reproductive (R) stages, in an exponential model.

Insect	Stage	Characteristics of spatial distribution models						
		[1]SSR	[2]C_0	[3]C_0+C	[4]Ao(m)	[5]R^2	[6]C_0/(C+Co)	LSD
S. graminum	V	1964897	1750	14770	10.70	0.40	0.11	Strong
	R	3603501	1320	12750	17.40	0.64	0.10	Strong
C. septempunctata	V	0.15	0.09	1.66	11.20	0.13	0.05	Strong
	R	0.04	1.38	2.91	308.90	0.84	0.47	Moderate

[1]SSR = sum of squared residual. [2]C_0 = nugget effect. [3]C+C_0 = sill. [4]Ao(m) = range. [5]R^2 = determination coefficient. [6]C_0/(C+Co) = the level of spatial dependence (LSD).

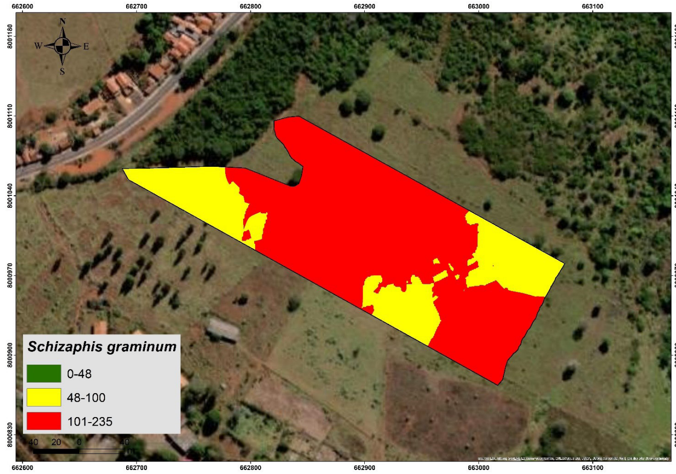

Figure 4. Spatial distribution of the pest *Schizaphis graminum* in sorghum crop in the vegetative stage. Values express the modeled absolute number of individuals.

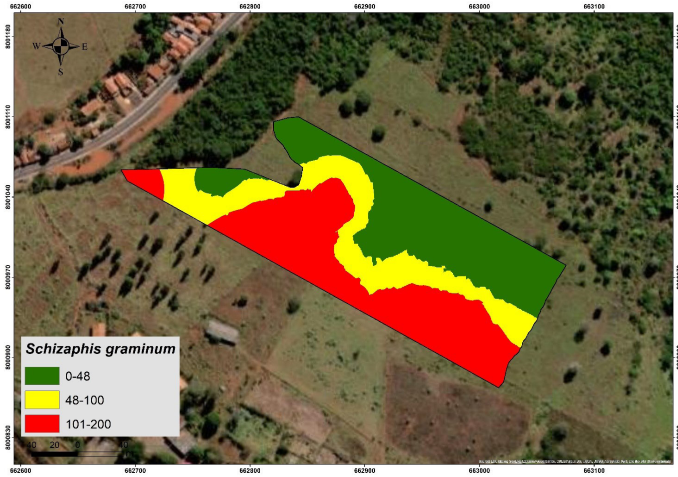

Figure 5. Spatial distribution of the pest *Schizaphis graminum* in sorghum crop in the reproductive stage. Values express the modeled absolute number of individuals.

evaluated, the spatial distribution occurred in concentrated patches, with an increase in densities towards the center of the crop.

For the natural enemy, *C. septempunctata,* the vegetative and reproductive stages distributions are shown in Figures 6-7, respectively.The incidence of *C. septempunctata* was not significant along the entire length of the crop. There was a concentration located in the western region of the area (Figure 6). The population grew significantly in the reproductive phase, expanding the incidence to the southern borders, in addition to remaining in the western part of the area (Figure 7)

In the reproductive stage, there was a higher incidence of *C. septempunctata* concentrated in places where there was also a higher population of the pest *S. graminum*. In both stages evaluated, the spatial distribution occurred in the form of patches, concentrating on the borders and with few foci in the central region of the crop.

4. Discussion

This study verified that the densities of *S. graminum* and its natural enemy *C. septempunctata* were influenced by the sorghum stage and the precipitation. The aphid population in the sorghum vegetative stage was more significant than in the reproductive stage, a plausible behavior since it is at this stage that the sorghum plant presents the most mature sheaths and low leaves, the preferred feeding site for this aphid species (Mendes et al., 2012)

The aphid population increased during the plant vegetative stage, and there was a reduction during the reproductive stage. On the other hand, its natural enemy maintained its population densities in both plant stages. Generalist predators such as *C. septempunctata* can be more affected by habitat fragmentation than prey population reduction (Ryall and Fahrig, 2006; Kianpour et al., 2011). Despite the population reduction of *S. graminum* during the *S. bicolor* reproductive phase, the presence of other prey

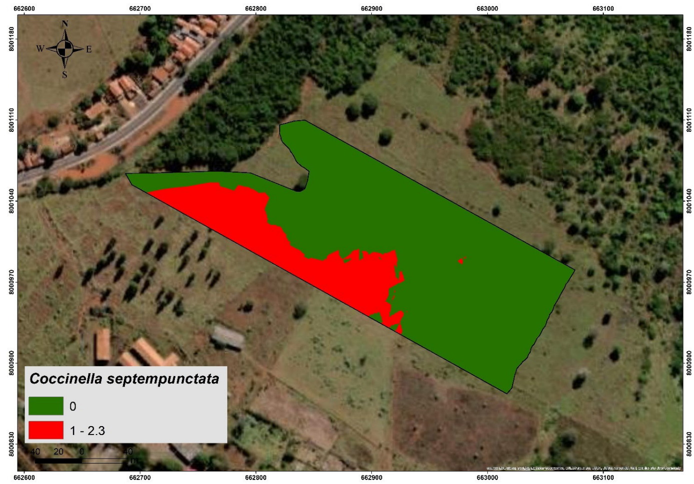

Figure 6. Natural enemy spatial distribution *Coccinella septempunctata* in sorghum crop in the vegetative stage. Values express the modeled absolute number of individuals.

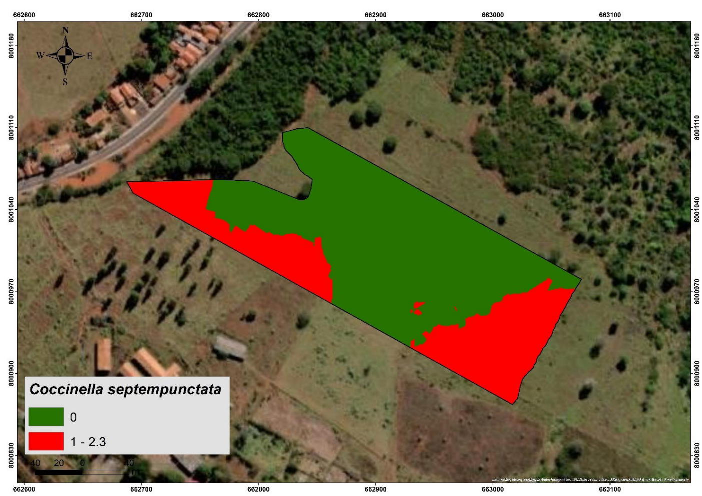

Figure 7. Natural enemy spatial distribution *Coccinella septempunctata* in sorghum crop in the reproductive stage. Values express the modeled absolute number of individuals.

species can guarantee the stability of the *C. septempunctata* population.

In addition, this reduction in pest density may still be linked to greater precipitation in the area in the reproductive stage, this inverse relationship between aphid population peak and rainfall has been reported in the literature (Schuber et al., 2009). After all abiotic factors may be the most important in the management of cereal aphids under field conditions (Mohanny et al., 2020; Benevenute et al., 2012). The rainfall of the Experimental Farm in the sorghum vegetative stage was 7 mm, whereas 253 mm was recorded for the reproductive stage (Figure 3). This increase in precipitation may justify the fall in the aphid population peak, as the impact of raindrops can carry some individuals.

Since the population density of natural enemies is dependent on the pest density incident on crops (Letourneau and Altieri, 1983), the positive and significant correlation in the reproductive stage between pest and predator, as shown in this study may be linked to the signaling mechanism of the predator-plant-pest interactions. The infested plant emits a pheromone to "warn" in response to pest attack. At the same time, the aphid also releases an alarm pheromone when it is being preyed upon, which attracts the ladybugs. Therefore, where the pest occurs, there will be the incidence of its natural enemy afterwards (Fontes and Valadares-Inglis, 2020).

However, this dependence between pest insect populations and their natural enemy may be associated with other ecological relationships between them, such as the induced resistance of sorghum, as a result of injuries, damage, or stresses that reduce the preference or performance of the herbivore, in this case, *S. graminum* (Gomes et al., 2004; Karban and Myers, 1989)

Natural enemies are important in the natural biological control of pests and can influence the population dynamics of these herbivores (Rosado et al., 2015). Ladybugs have a high potential for pest control, which drives several studies worldwide, but it is a highly competitive species capable of devastating other native coccinellids (Fontes and Valadares-Inglis, 2020). This predator instinct can also justify the dependence among the evaluated populations. Where there is food, there is likelihood of the presence of its predator.

The higher general incidence of the aphid in the north, south, and west of the area may also be related to the surrounding landscape because the winged aphids can fly hundreds of kilometers with the help of the prevailing wind (Gassen, 2002). In these regions, there were no tall plants that acted as windbreaks. In the northern region, there was a highway, in the south a rural road, and in the west a pasture with brachiaria. (Figure 1).

5. Conclusions

The spatiotemporal distribution of *S. graminum* was influenced by the stage of development of the sorghum, the surrounding landscape and the presence of its predator *C. septempunctata*. On the other hand, the density of *C. septempunctata* was influenced only by the increase in the density of the *S. graminum*. These results provide essential information for sorghum producers in crop planning, such as choice of area for cultivation, growing periods, and use of control methods in favor of predators for optimal aphid management.

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