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Decision-making for thrips control in soybean fields using precision agriculture principles

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Abstract

In precision agriculture, sub-areas of fields with similar features are called management zones and the inputs applied similarly in these zones. Such notion of management zones is applicable to high-output soybean fields where thrips are an emerging problem leading to losses up to 15%. Management zones are an agricultural management strategy that can be used for decision-making for controlling thrips on soybean fields. Thus, a 2-year study was carried out on commercial soybean fields aimed at developing a decision-making system for controlling soybean thrips using management zones. Three control programmes were established and assessed: CI-conventional control with insecticide use in the entire field; IPM-CS-conventional sampling plan + spray upon reaching the economic injury level (EIL; 3.43 thrips/sample); and IPM-MZ-spraying only specific areas of the field where thrips density reached the EIL. The decision to control reached using the IPM-CS and IPM-MZ programmes was 3× lower than those of the CI, which incurred in 75% mode decision mistakes. Furthermore, the decision to spray insecticides based on analysis of data for CI was also incorrect. In 8.5% (3.6% of treated and 4.9% of non-treated) of the field, the decisions of the IPM-CS programme were incorrect. The total cost of the CI programme (US$ 11.4/ha) was higher than that of the IPM-CS and IPM-MZ programmes (US$ 3.2 ha^{-1}). Therefore, owing to its technical, economic, and environmental advantages, the establishment of management zones seems worthy of incorporation in integrated thrips management decision-making systems for soybean fields.

KEYWORDS
control cost, control errors, *Glycine max*, integrated pest management, management zones

1 | INTRODUCTION

Soybean (*Glycine max* (L) Merrill) is the most widely planted legume in the world (Pagano & Miransari, 2016; Schimmelpfennig & Ebel, 2011; USDA, 2022). The world production of soybeans was 352.74 Mt in 2021/2022 and will increase by 11% in the next harvest year (USDA, 2022). A standing demand for world food production is to achieve high yields, reduce costs, and preserve the environment while growing crops (Liliane & Charles, 2020); this demand encourages the adoption of precision agriculture. Farmers have adopted precision agriculture technology tools such as GPS in tractors for scouting, variable rate applications and mapping yield in soybean (Schimmelpfennig & Ebel, 2011; Thompson et al., 2021). However, some challenges limit the adoption of precision agriculture systems, such as high cost, lack of skills coupled with absence of qualified agronomic services, inadequate sampling, non-availability of site-specific recommendations, and misuse of information (Pathak et al., 2019; Robert, 2002). In addition, use of precision agriculture principles in pest control is also limited. Neotropical soybean fields afford a promising scenario to circumvent this shortcoming due to their large extension and presence in different biomes, where it is attacked by different key pest species with significant losses.

Thrips (Thysanoptera: Thripidae) are considered emerging pests and the species belonging to genera *Caliothrips* and *Frankliniella* have been reported to damage soybean (Gamundi & Perotti, 2009; Santos et al., 2021). In recent years, soybean thrip densities have increased, causing up to 15% loss (González et al., 2017; Santos et al., 2021). Thrips are present throughout the soybean growing season (Selig et al., 2016), and cause damage by sucking cellular contents, injecting toxins, and acting as vectors of plant virus (Gent et al., 2004; Pereira et al., 2020).

In precision agriculture systems, variation in characteristics between and within fields influence decision-making in crops. In these systems, agricultural inputs are used according to the requirement of plants in each location/area in the field (Duhan et al., 2017; Singh, 2010). These systems contribute to increase crop yield, reduce costs, and lessen the environmental impact of agricultural inputs (Duhan et al., 2017; Whelan & Taylor, 2013). The characteristics of each field can be evaluated by the following methods within the context of precision agriculture: direct observation, sensors, yield monitoring, and tools like global positioning systems (GPS), and geographic information systems (GIS) (Basso et al., 2001; Bongiovanni & Lowenberg-Deboer, 2004). Those tools are used to obtain the information necessary to build the maps.

The maps resulting from these methods show the variation in field characteristics and are developed from the collected data and its geographic positioning coordinates. The use of these tools allows the recognition of sub-areas of the production fields exhibiting similar characteristics, which are referred to as management zones and receive similar agricultural inputs (Gavioli et al., 2019; Méndez-Vázquez et al., 2019). Such notion seems particularly useful for larger production systems of valued agricultural commodities, such as soybean.

The high dynamism of pest populations makes mapping zoning factors and response variables complex and laborious, consuming more resources (Méndez-Vázquez et al., 2019). Furthermore, the division of crop fields for pest management requires considering temporally dynamic zoning factors rather than stable ones (Méndez-Vázquez et al., 2019). Because pests do not have the characteristics of remaining uniform over time, the same principle as management zones could be understood as insecticide application zones for pest control to receive similar agricultural inputs.

Implementing homogeneous zones for pest management in agriculture involves identifying areas within a field that share similar characteristics or exhibit consistent patterns of infestations. The spatial distribution of insect populations can be aggregated, uniform, or random (Lima et al., 2018; Pereira et al., 2020). Insect spatial patterns manifest inherent biological characteristics (e.g., feeding, mating, dispersal) that are influenced by host plants and the environment (Pereira et al., 2020).

Despite the importance of thrips, there are no studies on the use of management zones for these pest species. This study aimed at tackling this limitation by using precision agriculture principles to propose a decision-making system for controlling thrips using management zones in the field.

2 | MATERIALS AND METHODS

2.1 | Soybean fields

The data used in this study were collected from four commercial soybean fields cultivated over 2 years (2017–2018 and 2018–2019 harvests) in the state of Tocantins, Brazil. These fields are in the savannah-like cerrado biome, which exhibits significant area under soybean cultivation under a tropical climate with rainy summers and dry winters (Alvares et al., 2013) (Table 1).

The cultivar M 8808 IPRO developed with Intacta RR2 Pro® technology with determinate growth was used in this study. Those cultivars were chosen due to their resistance against the main soybean caterpillar, resistance to lodging, and tolerant to the herbicide glyphosate for weed management. A spacing of 0.45 m was adopted between rows and 13 plants were maintained per meter row. Agronomic practices were carried out according to recommendations (Sediyama et al., 2015).

2.2 | Pest control programmes

Three treatments were simulated for thrips control in soybean. The first programme consisted of conventional control following

TABLE 1 Studies in different fields, locations, sizes and seasons are stated below.

Field	Location	Area (ha)	Seasons
A	11°55′23.80″ S and 49°41′40.70″ W	24.88	April to August 2017
B	11°48′10.30′′ S and 49°00′29.30′′ W	18	December 2017 to March 2018
C	11°49′2.80″ S and 49°39′1.40″ W	7.12	June to September 2018
D	11°45′20.90″ S and 48°51′ 24.20″ W	15.84	November 2018 to March 2019

calendar sprays of insecticide over the entire area (CI). This was chosen because it is most commonly practice used by farmers in the Brazilian cerrado (Bueno et al., 2021; Zalucki et al., 2009). The second programme is the conventional sampling proposed by Santos et al. (2021) for thrips on soybean and based on economic injury level (EIL) (EIL = 3.43 thrips/sample), as determined by Neves et al. (2022) (IPM-CS). This system involved spraying the entire field when the thrips density reached levels equal to or higher than the EIL (Bacci et al., 2008; Pedigo et al., 2021). The third programme involved spraying according to management zones (IPM-MZ). In this programme, the sprays were initiated for the subarea of the field where thrips density was equal to or higher than the EIL.

2.3 | Data collection

The density of thrips was evaluated by beating the plants and keeping a white plastic tray (32 × 24 × 7 cm) underneath to count the insects. The sampling unit consisted of one plant per beating. This technique is suitable for estimating thrips density in soybean (Santos et al., 2021). In field A, thrips densities were estimated when the plants reached the soybean phenological stages according to BBCH Scale (Biologische Bundesanstalt, Bundessortenamt and Chemical industry; Bleiholder et al., 2001) 16-106 (Trifoliolate leaf on the 5th node unfolded), 65-605 (full flowering: about 50% of flowers open), 73-703 (beginning seed/ Beginning of pod filling) and 77-707 (Advanced pod filling). In field B, the densities were assessed when the plants reached the stages 15-105 (Trifoliolate leaf on the 4th node unfolded), 16-106, 65-605, 73-703, and 77-707. In field C, the densities were estimated when the plants were in stages 15-105, 16-106, 65-605, 71-701 (beginning of pod development), 73-703, and 77-707. Finally, in field D, densities were assessed when the plants reached the stages 15-105, 16-106, 65-605, 71-701, 75-705 (full pod), 73-703, and 77-707. The position of each plant was georeferenced using GPS (Garmin Etrex Vista; Garmin, Lenexa, KS, USA). In the IPM-CS programme, thrips densities were determined by inspecting 40 plants per field. Santos et al. (2021) reported that this sampling is suitable for conventional plans to assess thrips densities in soybean. In the IPM-MZ programme, 200 plants per soybean field were inspected in a regular grid to determine the density of thrips. At each point, one plant was evaluated; this plant was marked with an identification tape, and the same plant was assessed throughout the season. This was done to ensure adequate sampling for the spatial distribution mapping of insects in the fields to establish management zones (Cid-Garcia & Ibarra-Rojas, 2019; Rosado et al., 2015).

2.4 | Establishment of management zones in soybean fields

Semivariograms were estimated using data from thrips densities in 200 plants per field (Pereira et al., 2020). Empirical data were fitted to the Gaussian, Exponential, Spherical, and Linear theoretical models. In total, 66 models were built, and the most suitable for each dataset was selected based on less residual sum of squares (RSS), higher coefficient of determination (R^2) and on the parameters of cross-validation [lower values of intercept (β_0) and higher slopes (β_1)]. All selected models were isotropic in the directions of 0°, 45°, 90° and 135° and pointed to the magnetic north. Subsequently, these data were interpolated by the indicator kriging method to determine thrips densities in areas not sampled. Spatial distribution mapping of thrips in fields in each season was done using GS+ Geostatistics for Environmental Sciences software (version 7.0; Gamma Design Software, Plainwell, MI, USA) (Robertson, 1998). Two management zones, namely when thrips density was lower than the economic damage level (EIL = 3.43 thrips/sample) and when the density of thrips was equal to or higher than the EIL were established.

2.5 | Determination of characteristics to compare thrips control programmes

Errors in decision-making, sampling time and cost incurred for each of the management methods were determined. In the CI programme, it was assumed that insecticide will be applied over the entire area of the field (Bueno et al., 2021; Zalucki et al., 2009). In the IPM-CS programme, it was considered that blanket insecticide application is carried out in the entire field when the pest density was equal to or greater than the EIL of 3.43 thrips/sample (Neves et al., 2022; Pedigo et al., 2021). In the IPM-MZ programme, it was assumed that insecticides would be applied only in areas where the pest density was equal to or greater than the EIL (Gavioli et al., 2019; Méndez-Vázquez et al., 2019; Neves et al., 2022).

The calculation of the size of the areas for pest control in the spatial distribution maps was performed using the image manipulation procedure of the packages BiocManager (Morgan & Ramos, 2022) and EBImage (Pau et al., 2010), of the software RStudio: Integrated Development for R (Boston, MA, USA) (Rstudio Team, 2020). The maps were segmented into two regions, where white represented equal or larger densities than EIL and black when thrips densities were smaller than the EIL and each part was calculated in pixels (Silva et al., 2017). The area to be treated was calculated using Equation (1) from the figure depicted in pixels. The non-control area (ha) was calculated as the difference between the total and the treated areas.

$$\mathrm{CA} = \left(\mathrm{FAr}_i \times \mathrm{ACI}\right) / \mathrm{TIA} \quad (1)$$

where CA is the field area (ha) where pest control is indicated; FAr = total area (ha) of the soybean field; i = soybean field (A, B, C, or D); ACI = Image where pest control is indicated (pixels); and TIA = total image area (pixels).

The percentage area with or without indications of thrips control is calculated using formulas (2) and (3).

$$\mathrm{PCt}_{ijz} = \left(100 \times \mathrm{CtA}_{ijz}\right) / \mathrm{FAr}_i \quad (2)$$

where PCt is the percentage of field area where pest control is indicated; i = soybean field (A, B, C, or D); j = stages of soybean plants; z = management approach (CI, IPM-CS, or IPM-MZ); CtA = area (ha) of the field in which thrips control is indicated; and FAr = total area (ha) of the soybean field.

$$PNC_{jz} = (100 \times CNA_{ijz}) / FAr_i \tag{3}$$

where PNC is the percentage of field area where pest control was not indicated; i = soybean field (A, B, C, or D); j = stages of soybean plants; z = management approach (CI, IPM-CS, or IPM-MZ); NCA = area (ha) of the field in which thrips control was not indicated; and FAr = total area (ha) of the soybean field.

The IPM-MZ programme was used as the standard to determine decision-making errors because the characteristics of each field location were determined (Gavioli et al., 2019; Méndez-Vázquez et al., 2019). When decisions for the CI and IPM-CS programmes were different from those selected by the IPM-MZ programme, the decisions of CI and IPM-CS were considered incorrect. The percentages of the area where errors occurred in the control decision using the CI and IPM-CS programmes were calculated using formulas (4) and (5).

$$CE_{ijz} = (100 \times CEA_{ijz}) / FAr_i \tag{4}$$

where CE is the percentage of field where errors occur in pest control decision; i = soybean field (A, B, C, or D), j = stages of soybean plants, z = control programmes (CI or IPM-CS), CEA = area (ha) of the field where errors occurred in pest control decision, and FAr = total area (ha) of the soybean field.

$$NCE_{ijz} = (100 \times NCEA_{ijz}) / FAr_i \tag{5}$$

where NCE = percentage of field where errors in pest control decision occurred because the pest was not controlled; i = soybean field (A, B, C, or D); j = stages of soybean plants; z = control programmes (CI or IPM-CS); NCEA = area (ha) of the field where errors in pest control decision because the pest was not controlled, and FAr = total area (ha) of the soybean field.

Sampling times were recorded to evaluate thrips densities in each field using the IPM-CS (40 plants) and IPM-MZ (200 plants) programmes. Next, the sampling, control, and total costs of the three programmes were calculated. Sampling costs included material (pencil, eraser, paper, and clipboard) and labor, calculated according to Santos et al. (2021). Control costs included chemical products (insecticides and adjuvants) and tractor spraying, calculated according to Neves et al. (2022). Finally, the total cost was obtained by adding the sampling cost to the control cost. All the graphical figures were created using the software Sigmaplot 12.5 (Systat Software Inc., 2013).

2.6 | Data analysis

R software (R Core Team, 2020) was used for data analysis. The data on the characteristics studied as a function of the control programmes were subjected to analysis of variance (α = 0.05). Characteristic means were compared using the Scott–Knott test at $p < 0.05$ (Jelihovschi et al., 2021; Scott & Knott, 1974). This test can be applied to data not having a normal frequency distribution (Borges & Ferreira, 2003; Jelihovschi et al., 2021). The data on the characteristics evaluated showed homogeneity of variance but did not have a normal frequency distribution.

3 | RESULTS

Of the 66 models estimated to determine the spatial distribution of thrips in soybean fields, 22 were selected. Of the 22 models selected, 21 had a nugget and plateau effect and one had a nugget effect. Of the models with plateau and nugget effects, 14 were Gaussian and seven were exponential. All models selected with threshold and nugget effects showed a strong spatial dependence (Spatial dependence rate (SDR) < 75%). The ranges of the spatial distribution models for thrips in field ranged from 9.35 to 53.34 m (Table 2).

Two management zones, namely when thrips density was lower than the economic damage level (EIL = 3.43 thrips/sample) (No control area) and when the density of thrips was equal to or higher than the EIL (Control area) were established for each field (Figure 1). The field's average pest densities ranged from 0.07 to 8.52 per sample. Even at the time of lowest occurrence, the density in the field subareas was higher than the EIL (EIL = 3.43 thrips per sample). The size of sub-areas with densities above the EIL increased as the average field density of thrips increased. The sub-areas with densities above the EIL occurred in both the central part and borders of the fields (Figure 1).

The sizes of the field subareas where there was an indication of thrips control varied according to the pest control programme. The areas indicated for thrips control by the IPM-CS and IPM-MZ programmes were about 3× smaller than those indicated for CI programme (Figure 2a).

In 75% of the situations, the indicator to take up spraying by the CI programme was wrong. In 8.5% of cases, the decisions taken by the IPM-CS programme were incorrect. Of these, 4.9% errors were on account of decisions regarding non-spraying and 3.6% were due to spraying (Figure 2b).

Thrips sampling time was significantly longer (df = 42, $p < 0.001$) in the IPM-MZ programme than that in the IPM-CS programme (Figure 3). The sampling cost of the IPM-CS programme was significantly higher (df = 42, $p < 0.001$) than that of the IPM-MZ (Figure 4a). The cost of sampling + sprays in the CI programme was significantly higher (df = 63, $p < 0.001$) than those of the IPM-CS and IPM-ZM programmes.

The total cost of the CI programme was approximately US$ 11.4 per ha while the costs of the IPM-CS and IPM-MZ programmes were US$ 3.26 and US$ 3221 per ha, respectively (Figure 4b, c).

4 | DISCUSSION

Thrips population showed an aggregated spatial distribution in the field. This is demonstrated by the fact that 95% of the

TABLE 2 Characteristics of thrips spatial distribution models in four soybean fields over 2 years.

Field	Plant stage	Characteristics of spatial distribution models							
		Model	β_1	β_0	RSS	C_0	C_0+C	Range (m)	SDR
A	V5	Exponential	−0.159	2.02	0.077	0.129	2.265	32.4	0.943
	R2	Gaussian	0.461	1.47	3.00	0.87	5.47	51.44	0.841
	R5	Exponential	0.312	5.85	12.8	4.69	21.25	29.8	0.779
	R6	Gaussian	0.444	3.48	9.66	2.42	22.95	53.34	0.895
B	V4	Gaussian	0.678	0.91	3.78	0.51	4.428	31.7	0.885
	V5	Gaussian	0.799	0.81	6.23	0.54	7.896	30.48	0.932
	R2	Gaussian	0.546	2.59	9.17	2.3	17.85	28.75	0.871
	R5	Gaussian	0.76	0.32	0.839	0.241	2.028	28.62	0.881
	R6	Gaussian	−0.267	0.08	0.001	0.031	0.181	19.39	0.828
C	V4	Exponential	0.587	0.82	0.913	0.17	3.457	15.3	0.951
	V5	Exponential	0.838	0.17	0.156	0.038	1.635	10.8	0.977
	R2	Gaussian	0.726	0.25	0.395	0.292	2.66	9.35	0.89
	R3	–	−0.085	1.40	Pure nugget effect				
	R5	Gaussian	0.233	0.34	0.002	0.071	0.551	10.05	0.871
	R6	Exponential	−0.468	7.23	22.8	2.53	17.08	12.9	0.852
D	V4	Gaussian	−0.345	2	0.361	0.462	2.875	15.76	0.839
	V5	Gaussian	0.346	0.76	0.695	0.346	2.256	14.03	0.847
	R2	Exponential	0.551	0.43	0.336	0.011	1.541	46.2	0.993
	R3	Gaussian	0.678	0.73	0.147	0.451	3.392	14.38	0.867
	R4	Exponential	0.256	5.66	800.00	10.70	60.80	16.5	0.824
	R5	Gaussian	−0.244	2.92	0.108	0.861	3.977	16.63	0.784
	R6	Gaussian	0.065	0.45	0.065	0.178	0.943	28.23	0.811

Abbreviations: β_0, curve intercept; β_1, slope of the curve; C_0, nugget effect; $C+C_0$, plateau; RSS, residual sum of squares; SDR, spatial dependence rate.

spatial distribution models showed sill, low nugget effects, and a strong spatial dependence (SDR < 75%) (Lima et al., 2018; Rosado et al., 2015). The interactions among insect mortality, migration, and birth contribute to the aggregation effect in spatial distributions (Aliakbarpour & Rawi, 2011; Pereira et al., 2020). The aggregation brings benefits, such as protection against natural enemies, increased efficiency in resource use, and the creation of a favourable microclimate for the clustered individuals (Bengtsson, 2008; Sword, 2008). In addition, the spatial distribution pattern of the pests in the field influences the sampling plan (Ghaderi et al., 2018; Waters, 1959).

The areas indicated for the control of thrips by the programme with the application of insecticides across the entire length of the fields were about 3× larger than the areas indicated for non-treatment using sampling plan and economic damage levels based in management zones. The excessive use of insecticides causes environmental impacts due to residues in soil, air, and water, and exposure to humans, natural enemies, pollinators, and wild animals (Boiça Júnior et al., 2007; Reitz et al., 2020; Santos et al., 2021). The correct prediction of the areas where the control of thrips should be performed is essential to reduce the cost and the impact of unnecessary insecticide application. In this context, using a sampling plan and EIL in management zones targeting specific areas did not show significant differences in control costs.

Blanket application of insecticides accounted for 75% of incorrect decisions, revealing that farmers should invest more in pest sampling to reduce unnecessary application and its high cost (Bueno et al., 2021; Kumar et al., 2019; Picanço et al., 2007). The use of a sampling plan and the EIL accounted for only 8.5% incorrect decisions. This demonstrates that using precision agriculture principles in pest control decision-making brings about economic and environmental benefits. In 4.9% of the areas, there was an indication to not control thrips, when it was necessary. These incorrect pest control decisions cause economic yield loss (González et al., 2017; Santos et al., 2021). However, in 3.6% of the areas, there was an indication for thrips control when it was not necessary. These incorrect decisions in not controlling the pest when required result in excessive use of insecticides and environmental harm (Miranda et al., 2005; Tang et al., 2010).

The cost of insecticide alone accounted for 92.5%–95.6% of the total cost incurred for controlling thrips. On the other hand, the sampling cost had little influence on the total cost of thrips control because it represented only 4.4%–7.5% of the total cost. Thus, the total cost of the programme including the insecticide cost of application

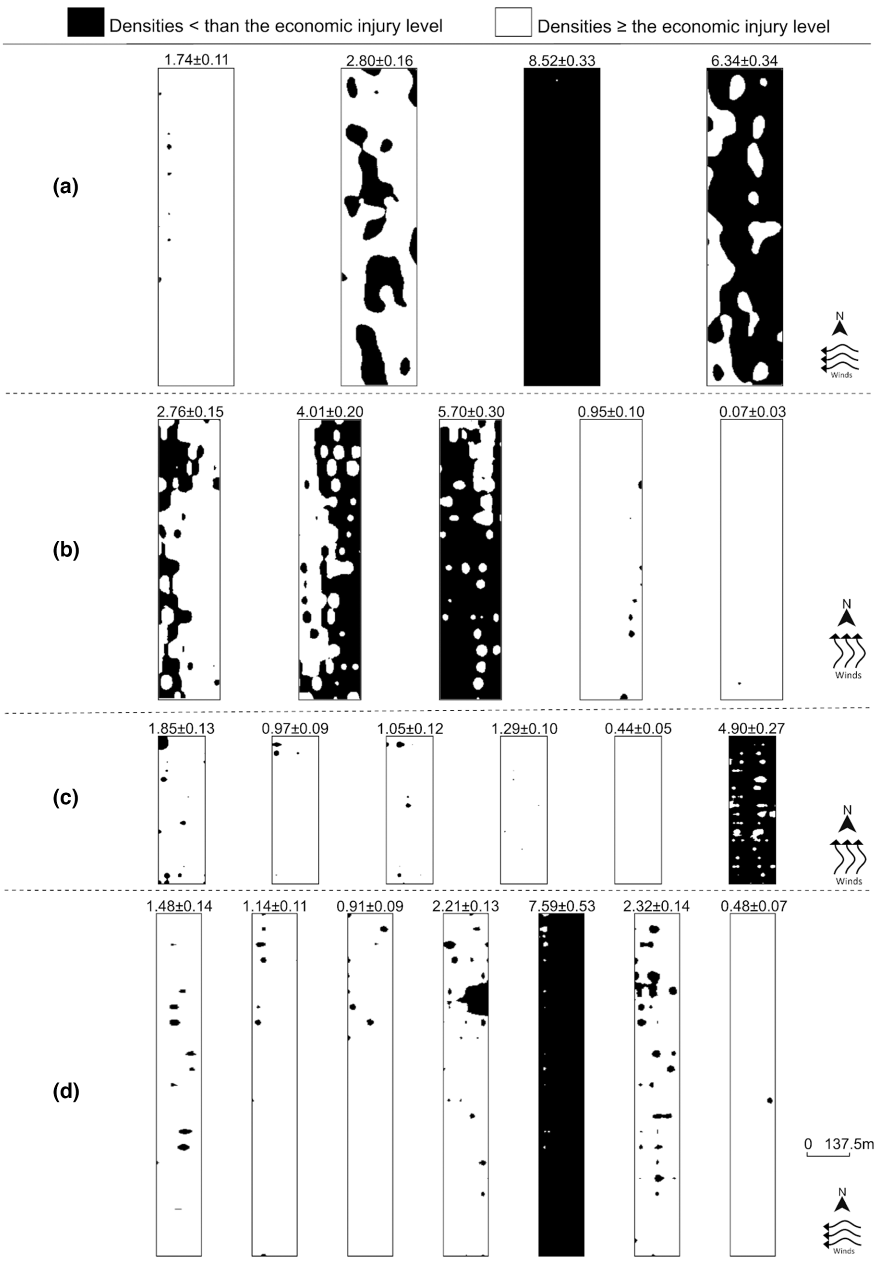

FIGURE 1 Spatial distribution maps of thrips in commercial soybean crops over 2 years. Two management zones, namely when the thrips density was lower than the level of economic damage (EIL = 3.43 thrips/sample) (area in which control is not necessary), are represented by white and when the thrips density was equal to or greater than the EIL (area in which control is needed), they are represented by black for each field.

in the whole area without sampling represented the highest cost. This was so because this approach used three times more insecticides than when management zones were used combined with a sampling plan and the EIL. Therefore, it is advantageous to adopt a management plan that considers decision-making systems to control thrips, which reduces consequent environmental impact by about 70%. These economic and environmental advantages are essential for the sustainability of agricultural production systems (Bottrell & Schoenly, 2018; Castle & Naranjo, 2009). This allows farmers to earn greater profits (Ahuja et al., 2015; Kibira et al., 2015) and to conserve non-target organisms such as natural enemies and pollinators (Egan et al., 2020; Picanço et al., 2007). In addition, decreased insecticide use reduces the selection of insecticide-resistant insect populations (Onstad, 2014; Umina et al., 2019), and primary and secondary pest outbreaks (Reitz et al., 2020).

Resistance management may benefit from keeping susceptible insecticides in unapplied areas. This approach can help to reduce, or even prevent evolution of resistance in the applied areas (Betancur, 2018). By using insecticides only when control by natural enemies cannot limit economic damage, the development of resistance can be slowed (Denholm et al., 1998). The increasing severity of resistance on pest and disease management programmes highlights the need for strategies designed to circumvent the impact of resistance on pest management (Mallet, 1989).

The pest control programme based on management zones reduces the wrong decisions, showing more accuracy than the other methods evaluated in this study. Besides that, previous studies reveal that thrips populations in soybeans do not seem to vary depending on the characteristics of the host plant, nor biotic and abiotic factors, being affected only by rain and photoperiod (Santos

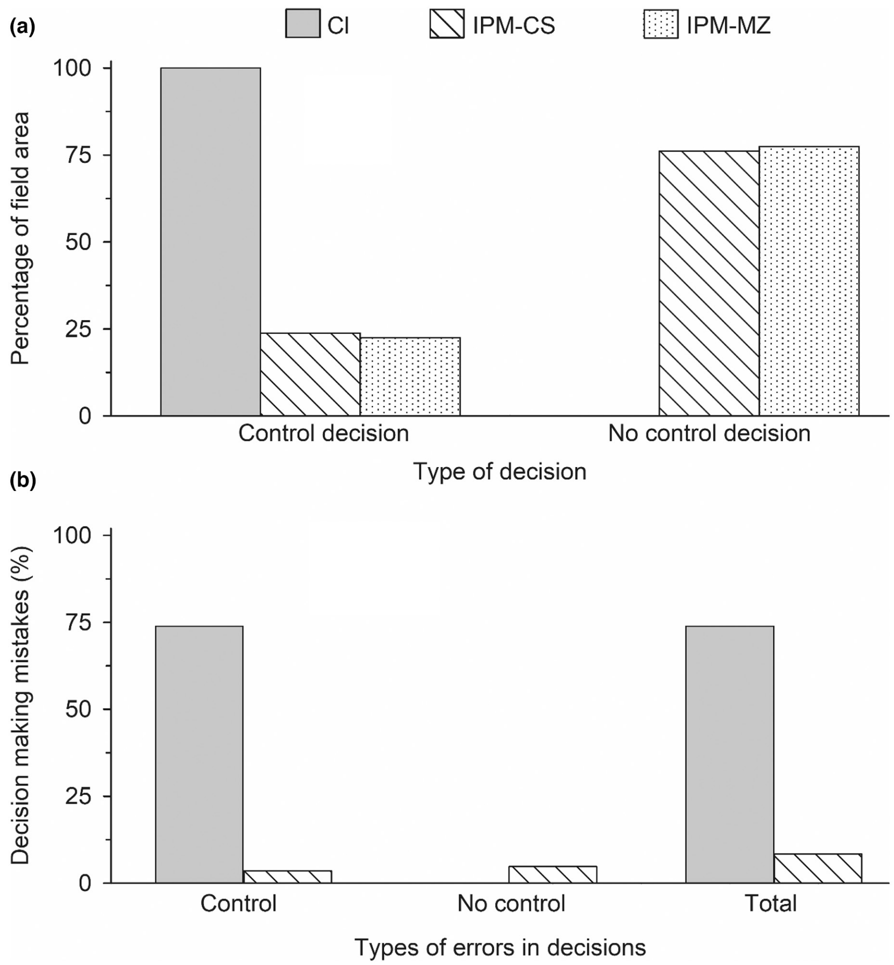

FIGURE 2 (a) Percentage of soybean field areas where thrips control should or should not be carried out according to three approaches: CI (calendar schedule with insecticide application throughout the area), IPM-CS (conventional sampling plan and level of economic damage [EIL = 3.43 thrips/sample]), and IPM-MZ (control application only in the field area where the pest density reached the IEL [these areas are shown in the maps in Figure 1]). (b) Percentage of field areas where errors occurred in the control decision using the CI and IPM-CS programmes; in these comparisons, the IPM-MZ programme was used as the standard.

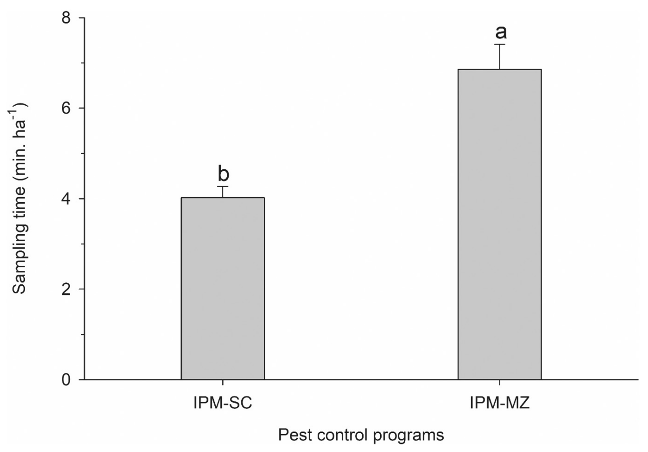

FIGURE 3 Time (mean ± standard error) of thrips sampling in soybean fields by IPM-CS (conventional sampling plan and economic damage level [EIL = 3.43 thrips/sample]), and IPM-MZ (control application only in the field area where the pest density reached the EIL [these areas are shown on the maps in Figure 1]). The histograms followed by the same letter do not differ from each other, according to the Scott–Knott test ($p < 0.05$).

et al., 2022). This makes thrips a suitable species to qualify for a study to control based on management zones. Furthermore, thrips seem to maintain an aggregated distribution, which facilitates the control process only in certain cultivation areas (Santos et al., 2022).

Producers can implement control in management zones by monitoring crop pests and identifying where the EIL has been reached. This information can be imported into the tractors' on-board computer for application only in areas where control is indicated. To obtain the maps, producers, and technicians would need a computer with the free programmes RStudio and GS+ installed and would have computer knowledge and an understanding of geostatistical analysis.

Although the decision-making method recommended in this work is the pest control programme based on management zones, as well as the other decision-making methods compared in this work, it does not exclude the need for constant sampling in the cultivation areas. Weekly sampling should continue in areas where control has not been done to verify if such areas will achieve the EIL. Periodic sampling should also be done in areas where control has been done to ensure pest populations remain below the EIL.

In conclusion, the decision-making approach of using management zones proposed in this study can be incorporated into integrated management system for thrips in soybean fields because leads to higher cost-effectiveness in the decision-making process This contributes to maximize soybean yield, reduce costs, and preserve the environment.

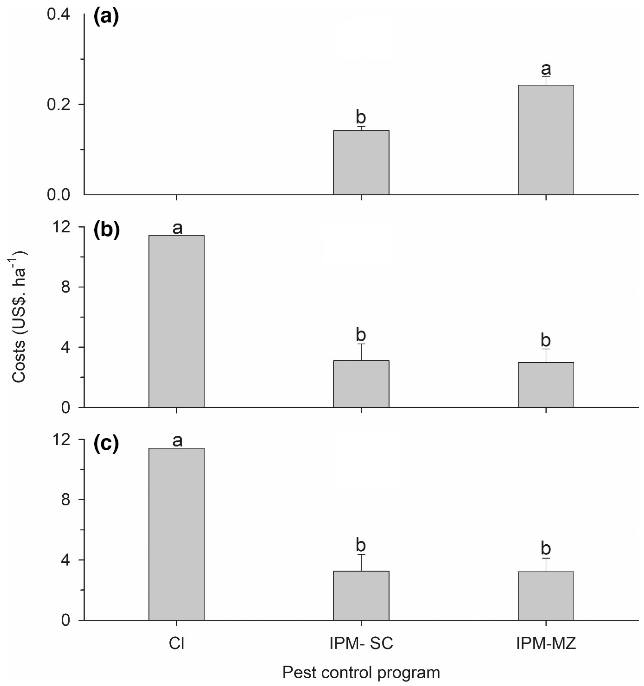

FIGURE 4 Costs (mean ± standard error) of (a) sampling, (b) control, and (c) total use of CI programmes (calendar schedule with insecticide application throughout the area), IPM-CS (conventional sampling plan and EIL [EIL = 3.43 thrips/sample]), and IPM-MZ (control application only in field area where pest density reached EIL [these areas are shown in Figure 1]). The histograms followed by the same letter do not differ from each other, according to the Scott–Knott test ($p < 0.05$).

AUTHOR CONTRIBUTIONS

Juliana L. Santos: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; writing – original draft. **Poliana S. Pereira:** Data curation; investigation. **Kayo H. B. Reis:** Data curation; investigation. **Marcelo C. Picanço Filho:** Data curation; investigation. **Damaris R. Freitas:** Data curation; investigation. **Joenes M. Peluzio:** Writing – review and editing. **Renato A. Sarmento:** Conceptualization; funding acquisition; supervision; writing – review and editing. **Raul N. C. Guedes:** Supervision; writing – original draft. **Marcelo C. Picanco:** Conceptualization; data curation; formal analysis; methodology; project administration; supervision; writing – original draft.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in 'Mendeley Data' at 10.17632/r3d7sv9v4m.1 (Santos, 2022).

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