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New Decision-Making Control System for Caterpillars on Soybean Fields

Poliana Silvestre Pereira [1], Mayara Cristina Lopes [2], Kayo Heberth de Brito Reis [1], Hugo Daniel Dias de Souza [1], Guilherme Pratissoli Pancieri [3], Marcelo Coutinho Picanço [3] and Renato Almeida Sarmento [1,*]

1 Graduate Programme in Plant Production, Federal University of Tocantins, Gurupi 77402-970, Brazil; poliana_silvestre@yahoo.com.br (P.S.P.); kayoheberthdebritoreis@gmail.com (K.H.d.B.R.); hugods444@gmail.com (H.D.D.d.S.)
2 Graduate Programme in Plant Production, University of Rio Verde, Rio Verde 75901-970, Brazil; mayara@unirv.edu.br
3 Department of Entomology, Federal University of Viçosa, Viçosa 36570-900, Brazil; guilhermepancieri@gmail.com (G.P.P.); picanco@ufv.br (M.C.P.)
* Correspondence: rsarmento@uft.edu.br

Abstract: Decision-making systems are essential to integrated pest management (IPM) programs, particularly in the context of soybean (*Glycine max*), the world's most cultivated legume. As agricultural practices change, including adopting new cultivars, planting seasons, and planting regions, the challenges in pest management, mainly caterpillars (Lepidoptera larvae), also change. To address this, this study aimed to devise an updated decision-making approach tailored to the current soybean field conditions. Over two years, caterpillar densities were evaluated in 38 commercial soybean fields. The beating tray sampling technique was superior in precision and efficiency compared to the direct counting and beating cloth techniques. This technique involved assessing 61 plants per field to determine caterpillar density. Economic thresholds were determined at 7.11 caterpillars per beating tray for vegetative stages and 3.60 for reproductive stages. The new proposed sampling system was validated and demonstrated more precise and representative caterpillar density determination than the standard beating cloth system. Both methods exhibited similar costs and execution times. Therefore, this refined decision-making system has the potential for incorporation into soybean IPM programs due to its accuracy, representativeness, feasibility, speed, and cost-effectiveness. This study underscores the viability of integrating the newly developed decision-making system to enhance soybean pest management strategies.

Keywords: decision-making system; soybean; Lepidoptera; sampling plan; economic threshold

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1. Introduction

Decision-making systems are essential components of integrated pest management (IPM) programs. These systems consist of sampling plans and decision-making indices [1,2]. The sampling plans evaluate the densities of pests and natural enemies [3]. These plans can be conventional or sequential [3,4]. The conventional sampling plans have a fixed number of samples per field, while in the sequential sampling plans, the number of samples per field varies depending on the pest density [4].

The first step toward developing a novel system of decision-making for pest control is the determination of a conventional sampling plan [3,5]. The sampling technique and number of samples per field are determined by this plan [3]. Furthermore, conventional sampling plans are used to determine the indices in the decision-making system and to validate the sequential sampling plans [3].

The sampling technique is the methodology (direct counting or using equipment such as beating cloth, trays, magnifying glass, and traps) used to assess the pest density [3]. The number of samples in the sampling plan must enable the pest density assessment to be carried out quickly, with low cost, accurately, and representatively of the absolute density of the insect in the field [3,5].

The main decision-making indices for decision-making systems for pest control are the economic injury level (EIL) and the economic threshold (ET). The EIL is the lowest pest density that causes economic damage [2,6]. The ET is the pest density at which the decision to control is taken to prevent the organism from reaching the EIL [6–8].

Soybean (*Glycine max* (L.) Merrill) is the most planted legume in the world. It is the main protein source in animal feed in the world and the second largest source for manufacturing vegetable oil [9]. As of the latest harvest (2022/2023), the world's soybean production was 370 million tons; Brazil is the world's largest producer of soybeans (with 154.6 million tons) [10]. In recent years, there have been many changes in soybean fields with novel cultivars, increased yields, and changes in the production system (spacing and fertilization), season, and planting regions. These factors affect decision-making systems [11,12].

Among the most essential groups of pests that attack soybean crops are caterpillars (Lepidoptera larvae). These pests damage plants by defoliating and attacking stems, flowers, pods, and grains [7,13]. In the past, the most abundant Lepidoptera species in soybean crops in the Neotropics was *Anticarsia gemmatalis* (Hübner) (Noctuidae). Currently, other Noctuidae species, such as *Chrysodeixis includens* (Walker), *Helicoverpa armigera* (Hübner), *Spodoptera cosmioides* (Walker), *Spodoptera eridania* (Cramer), and *Spodoptera frugiperda* (Smith), have been the most abundant [7,12–14].

For a technique to be selected for use in pest sampling, it must be accurate [15,16]. The beating cloth technique is the most commonly used method for sampling caterpillars in soybean fields [11,17]. This technique was proposed by Boyer and Dumas [18] and later adapted by Shepard et al. [15]. To calculate the number of samples in the conventional sampling plan, the frequency distribution of the pest density data must be determined, and the error allowed in the assessments must be established [3]. Another fundamental step in establishing a novel decision-making system is its validation. For this process, the novel system is compared in terms of accuracy, speed, and cost with the existing system [5,12]. Due to the changes in soybean crop management that have taken place in recent years and the abundance of Lepidoptera larvae species that attack this crop, the objective of this study was to propose a novel decision-making system to control these pests. To achieve this, the densities of caterpillars were monitored for two years in commercial soybean fields to determine and validate a conventional sampling plan and an economic threshold for these caterpillars.

2. Materials and Methods

2.1. Experimental Conditions

The work was conducted over two years (2017 to 2019) in commercial soybean fields located in Formoso do Araguaia (11°47′48″ S, 49°31′44″ W, 240 m altitude) and Gurupi (11°43′48″ S, 49°04′08″ W, 287 m altitude), in the state of Tocantins, Brazil. This region belongs to the Cerrado biome (the main biome in Brazil where soybeans are cultivated), and the climate of this region is tropical, with dry winters and rainy summers [19]. The variety M8808 IPRO with Intacta RR2 PRO® technology (J&H Seeds, Correntinha, BA, Brazil) was sown in the soybean fields. This variety has a determined growth, with a cycle of 140 days, is resistant to lodging, is tolerant to the herbicide glyphosate, and is resistant to some Lepidoptera species [20]. The crops were cultivated according to the recommendations of Sediyama et al. [21], with a spacing of 45 cm between rows and ten plants per meter in a row. Each soybean field had about 20 ha. Lepidoptera specimens observed attacking soybean plants were collected and stored in 100 mL glass bottles containing a 90% ethyl alcohol solution. Lepidoptera larvae species identification was performed using taxonomic keys [22] and compared with the existing specimens at the Museum of Entomology of the Federal University of Viçosa, Viçosa, Minas Gerais State, Brazil.

This work was divided into three parts. The best sampling technique and the economic thresholds were determined in the first part. The second part determined the number of samples in the conventional sampling plan. In the third part, the validation of the sampling plan was performed.

2.2. Selection of the Sampling Technique and Determination of Economic Thresholds

This part of the study was carried out in three soybean fields. In each, the plants were in the vegetative stage (V4) and in the beginning (R2 = flowering) and middle (R4 = fruiting) of the reproductive stage (Figure 1A). In each soybean field, a total of 200 plants were evaluated for each sampling technique. In each field, the area was divided into 100 sub-areas of 0.2 ha, and each one represented a repetition. In each repetition, the densities of caterpillars were evaluated using direct counting, beating cloth, and beating tray techniques. The three sampling techniques were randomly carried out in different areas of the plots. The beating cloth technique was used as a standard comparison because it is the most commonly used when sampling insects in soybean fields [11,23]. Meanwhile, the direct counting and beating tray techniques were also analyzed because they are widely used in the sampling plans of various groups of insects in crops of various cultures [24].

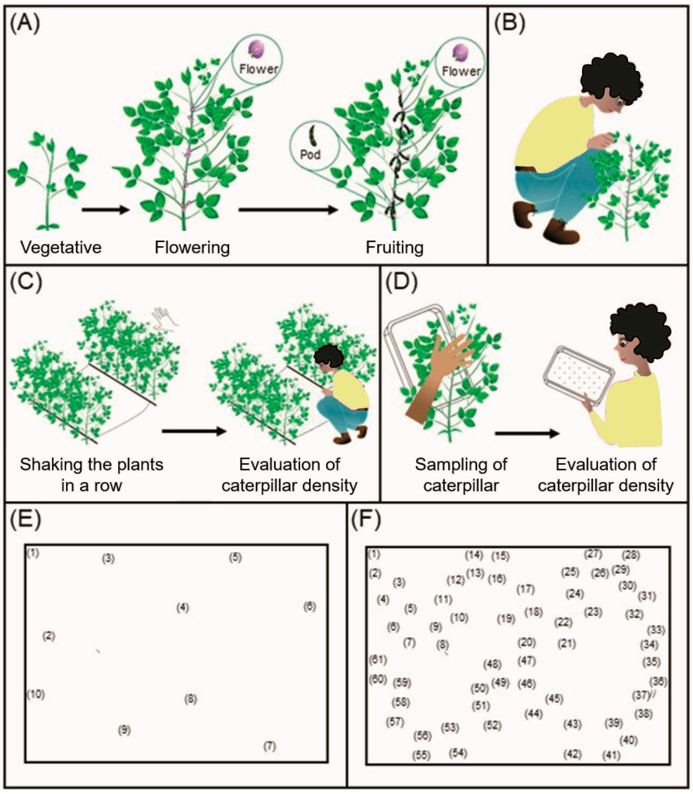

Figure 1. (**A**) Stages of the plants, use of the (**B**) direct counting, (**C**) beating cloth, and (**D**) beating tray techniques, and walking for a sampling of caterpillars in the sampling plans (**E**) used by farmers with 10 samples per plot and (**F**) determined in this work with 61 samples per field (adapted from Santos et al. [24]).

In the direct counting technique, the number of caterpillars present on all plant leaves was counted. In the beating tray technique, the plant was shaken inside a white plastic tray (40 × 25 × 3 cm), and the caterpillars present at the bottom of each tray were counted. In the beating cloth technique, a 1.0-meter-long white cloth was spread on the ground between two rows of soybeans. Then, the plants in a row were shaken into the cloth, and the number of caterpillars that fell on it was counted (Figure 1B–D). In each repetition, the time spent executing the sampling was recorded for every technique analyzed.

The standards of accuracy and speed were used to select the most efficient technique for caterpillar sampling [16,25]. They were used due to the need for a precise technique to determine a sampling plan with the smallest number of samples. Meanwhile, fast execution reduces the final cost of sampling because labor is the main component of those costs [16,25]. By the standard of accuracy, the techniques that presented relative variance (RV) lower than 25% were the ones selected. The RV was calculated using Formula (1):

$$RVji = 100 \times \frac{EPji}{xji} \tag{1}$$

where *RVji* = relative variance (%) for the technique *j* (*j* = 1: beating cloth; *j* = 2: direct count; and *j* = 3: beating tray) and the stage of plants *i* (*i* = 1: vegetative stage; *i* = 2: the beginning of the reproductive stage; and *i* = 3: the middle of the reproductive stage), *EPji* = standard error, and *xji* = average density of caterpillars.

Based on the speed standard, the technique that exhibits the shortest time for sampling was selected in each phenological stage. An analysis of variance ($\alpha = 0.05$) was performed on the sampling time data. The average time of each technique for the soybean plants was compared using the Tukey test at $p < 0.05$ in each phenological stage.

Next, the ET for caterpillars on soybean plants in the vegetative and reproductive stages was determined using the selected sampling technique. Therefore, a simple linear regression analysis was performed on the densities of the caterpillars sampled by the selected technique (beating tray) as a function of the densities sampled by the standard technique (beating cloth) at $p < 0.05$ [26]. Subsequently, in the equation of this curve, the economic threshold values for the beating cloth (the standard technique) were used in soybean plants in the vegetative (20 caterpillars per meter) and reproductive (10 caterpillars per meter) stages [17]. The two values derived are the ETs in soybean fields for Lepidoptera larvae when using the selected technique (in this case, the beating tray technique), with plants in the vegetative and reproductive stages.

2.3. Number of Samples from the Sampling Plan

The frequency distribution of the caterpillar densities in the soybean field was determined in this part of the study. For this purpose, the densities of these insects were evaluated in 12 soybean fields where those plants were in the vegetative stage (V4) and in the beginning (R2 = flowering) and middle (R4 = fruiting) of the reproductive stage. In each field, the densities of the caterpillars were assessed on 200 soybean plants using the previously selected technique (beating tray). The evaluated plants were distributed on a regular grid in the soybean fields so that the evaluations were representative of the spatial distribution of the insects in the area and to eliminate possible directional evaluation tendencies [24].

The means and standard errors of the caterpillar densities were calculated for each soybean field. The data obtained was used to calculate the frequency distribution and to verify if the observed and expected frequencies fit the negative binomial, Poisson, and positive binomial distributions [27]. The caterpillar density data fits a type of frequency distribution that happens when the observed and expected frequencies are not significant ($p > 0.05$) when using the chi-square test (2) [27]. This calculation defines the formula used to determine the number of samples necessary to compose the sampling plan. Therefore, the type of frequency distribution will only be defined when the insect density data that fits that distribution model occurs in the majority (≥70%) of the soybean fields. Thus, it will be verified that this distribution represents the data appropriately [3,27].

Thereafter, the aggregation parameter (k) for the frequency distribution of caterpillar densities was calculated in each of the 12 soybean fields using Formula (2):

$$k = \frac{x^2}{(S^2 - x)} \tag{2}$$

where k = insect aggregation parameter in the soybean field, x = mean caterpillar densities, and S^2 = variance of caterpillar densities. This formula suits insect species whose densities follow the negative binomial frequency distribution [27].

The value of parameter k was subjected to a simple linear regression analysis as described by Bliss and Owen [28]. According to their methodology, insect densities in soybean fields showed a common aggregation k value (kc) when exhibiting a significant slope and non-significant regression intercept by the F test (at $p < 0.05$) [28].

After obtaining the kc value, the number of samples was determined using Formula (3):

$$NA = \frac{1}{C^2}\left(\frac{1}{\mu} + \frac{1}{kc}\right) \quad (3)$$

where NA = sample number, C = permitted error, μ = population mean, and kc = common parameter of aggregation of the negative binomial frequency distribution, determined previously.

For this calculation, error values ranging from 5 to 25% were used. These values were used because they are appropriate for generating a representative decision-making system for IPM programs [25,27,29]. Therefore, the error adopted for the final calculation was the lowest error value for which there was little variation in the number of samples and allowed the generation of a feasible sampling plan. In other words, a sampling time that is up to one hour [27,29].

2.4. Decisions, Time, Cost, and Validation of the Use of the Sampling Plan and the Control Levels Determined by This Study

At this stage, the duration and cost of sampling caterpillars in 22 soybean fields of 20 ha each were determined using the beating tray (the one selected in this work) and the beating cloth techniques. Therefore, for the two sampling techniques, the distance traveled inside the area, the travel time between the samples, and the time spent for each evaluation technique in each field were evaluated. Based on the data obtained, the time and cost to perform a single sampling were calculated for both techniques. To calculate the sampling cost, Formula (4) was used:

$$CS = CM + (TS \times CL) \quad (4)$$

where CS = cost of 1 sampling, CM = cost of sampling material (pencil, eraser, paper, clipboard, white plastic tray, and beating cloth), TS = sampling time (h), and CL = labor costs (salary of a rural worker per h and social charges). To calculate the cost of materials, a durability period of one year was considered [27].

The sampling plan was validated by monitoring the caterpillars. Thus, the caterpillar complex was randomly sampled in the 22 commercial soybean fields using the sampling plan determined in this work (the beating tray technique) and the sampling plan currently practiced (the beating cloth technique). In each field, the sampling was carried out by the beating tray technique using the number of previously defined samples (61 samples) and the number of samples for the beating cloth technique (10 samples). Thus, for each sampling technique and in each field, the caterpillar density (mean $\pm$ standard error) was determined using the number of samples described above and the type of decision to be taken (control or non-control). In addition, the percentage of correct decision-making and the time savings resulting from adopting the proposed new sampling plan in relation to the sampling plan used were obtained [5].

3. Results

The Lepidoptera species observed attacking soybean plants in the fields were *Anticarsia gemmatalis*, *Chrysodeixis includens*, *Helicoverpa armigera*, *Spodoptera cosmioides*, *S. eridania*, and *S. frugiperda*, all from the moth family Noctuidae. The densities of caterpillars found in plants at the reproductive stage (fruiting) were higher than in plants at the vegetative stage and at the beginning of the reproductive stage (flowering) (Figure 2). The most abundant Lepidoptera species in soybean plants was *C. includens*, found at the vegetative stage and the beginning of the reproductive stage (flowering). In the reproductive stage (fruiting), the most abundant species was *S. cosmioides* (Figure 2).

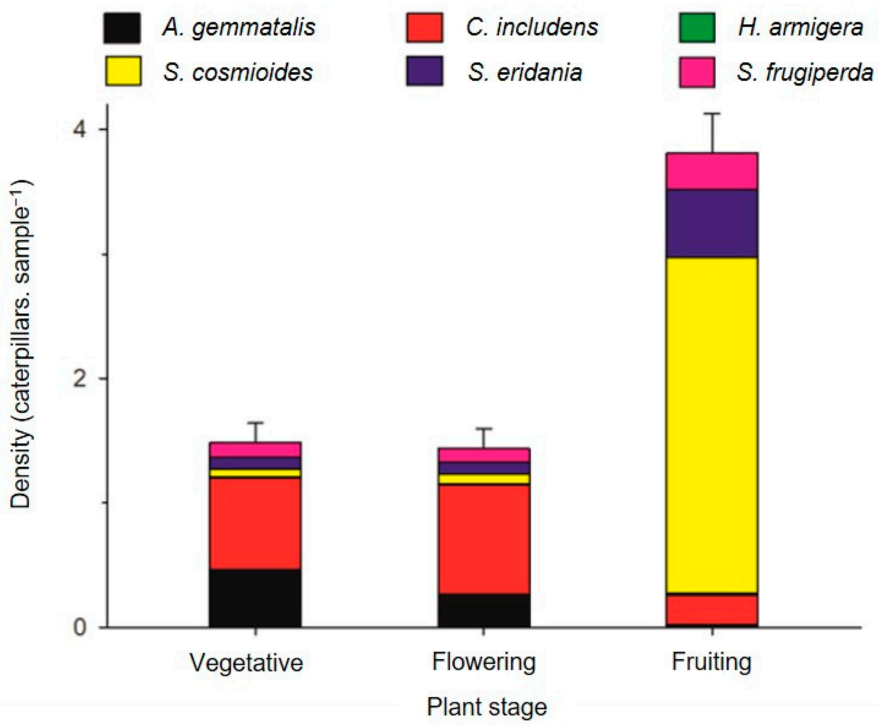

Figure 2. Densities (mean ± standard error) of Lepidoptera species observed in soybean crops with plants in the vegetative, flowering, and fruiting stages sampled by the beating tray technique.

3.1. Selection of Sampling Technique

According to the accuracy criterion, the direct counting and beating tray techniques were the most suitable for sampling the caterpillars on soybean fields. The densities evaluated presented relative variances lower than 25% in crops with plants in all stages. Otherwise, the caterpillar densities evaluated by the beating cloth technique only showed relative variances lower than 25% when the plant evaluated was in the middle of the reproductive stage (R4 = fruiting) (Figure 3A).

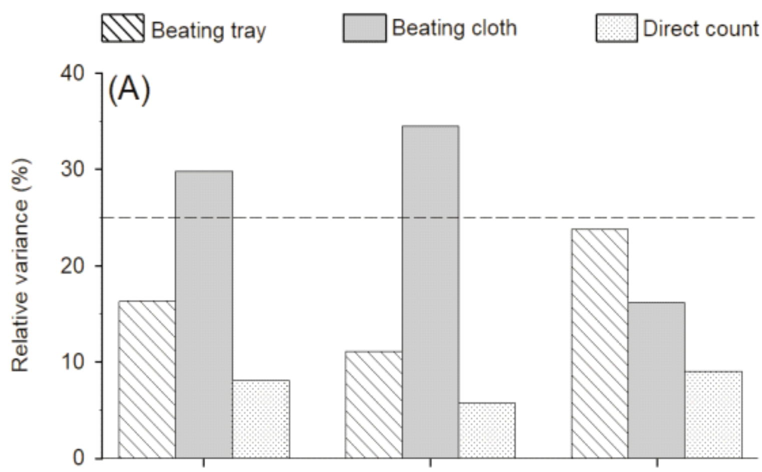

Figure 3. *Cont.*

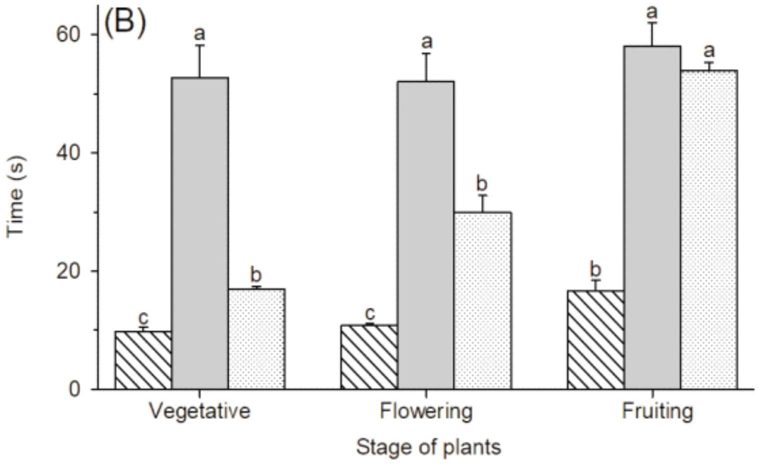

Figure 3. (**A**) Relative variance and (**B**) sampling time of caterpillars using three techniques in a soybean field with plants at different phenological stages. The sampling time is followed by different lowercase letters with means that differ from each other, according to Tukey's test ($p < 0.05$).

In soybean plants at all phenological stages, there was a significant slope (F = 67.94; df = 2.61; $p < 0.0001$) in the sampling time according to the technique used. At all stages of the plants, the fastest technique was the beating tray technique. The beating cloth technique took the longest time to execute, while the direct counting technique had an intermediate execution time compared to the other two techniques (Figure 3B).

3.2. Economic Threshold for Caterpillars with the Beating Tray Technique

It was found that the simple linear model of the densities of caterpillars sampled by the beating tray technique as a function of the densities sampled by the beating cloth was significant ($p < 0.0001$). In addition, this model showed a coefficient of determination of 94% ($R^2 = 0.94$) (Figure 4).

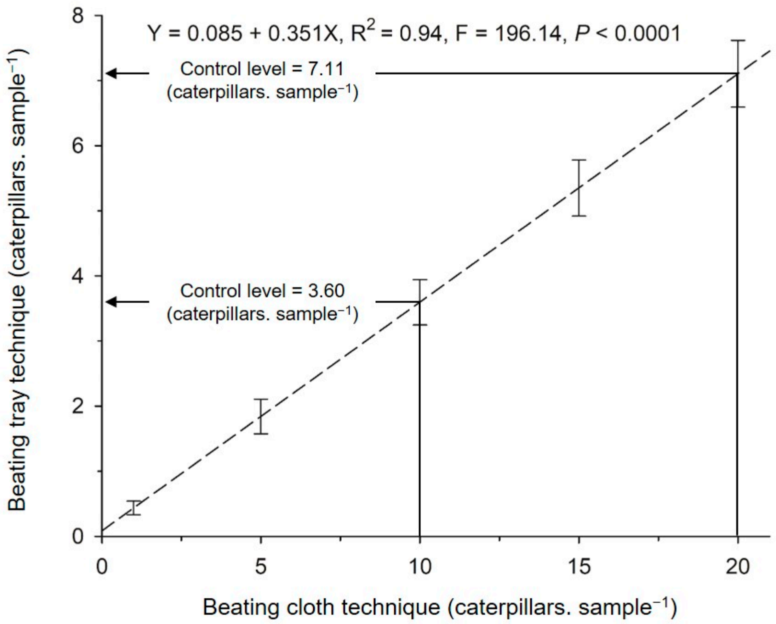

Figure 4. The density of caterpillars sampled by the beating tray technique as a function of the density sampled by the beating cloth technique. The vertical line segments represent the model's confidence interval at 95% probability.

Inserting into this equation the value of the economic threshold (ET = 10 caterpillars/sample and ET = 20 caterpillars/sample) for the beating cloth technique [11], it was determined that the

ET for the beating tray technique was 7.11 caterpillars/sample for plants in the vegetative stage and 3.60 caterpillars/sample for plants in the reproductive stage, respectively (Figure 4).

3.3. Frequency Distribution of Caterpillar Densities

The Lepidoptera larvae density data using the beating tray technique fitted the negative binomial frequency distribution in 83.33% of the situations, presenting non-significant chi-square statistics ($p > 0.05$) on 10 of the 12 fields evaluated. These densities only fit the Poisson distribution in one of the 12 evaluated fields (8.33%). Furthermore, in none of the fields did the caterpillar densities fit the positive binomial frequency distribution (Table 1). Therefore, the number of samples must be calculated using the formula for the negative binomial frequency distribution.

Table 1. Densities (mean ± error) evaluated by the beating tray technique, chi-square test (χ^2), and degrees of freedom (df) of observed and expected frequencies according to various frequency distributions (test χ^2).

Plot	Density (Caterpillar. Sample^{-1})	Negative Binomial		Poisson		Positive Binomial	
		χ^2	df	χ^2	df	χ^2	df
Crops with plants in the vegetative stage (V4)							
1	0.12 ± 0.03	0.69 ^{ns}	1	18.55 *	2	221.52 *	2
2	0.09 ± 0.02	0.20 ^{ns}	1	2.33 ^{ns}	1	135.98 *	1
Crops with plants at the beginning of the reproductive stage (R2 = flowering)							
3	0.07 ± 0.03	0.07 ^{ns}	1	99.34 *	2	90.57 *	2
4	0.12 ± 0.03	0.27 ^{ns}	1	22.27 *	2	212.54 *	2
5	0.19 ± 0.06	7.48 *	2	142.31 *	3	874.70 *	3
Crops with plants in the middle of the reproductive stage (R4 = fruiting)							
6	0.14 ± 0.04	9.18 *	1	13.01 *	2	445.32 *	2
7	0.10 ± 0.02	0.62 ^{ns}	1	5.53 *	1	146.22 *	1
8	0.41 ± 0.07	7.76 ^{ns}	3	83.81 *	4	1.9×10^4 *	4
9	0.33 ± 0.09	1.63 ^{ns}	2	244.33 *	3	1.8×10^3 *	3
10	1.52 ± 0.23	11.95 ^{ns}	8	4.0×10^4 *	9	4.9×10^7 *	9
11	0.20 ± 0.04	3.18 ^{ns}	2	149.36 *	3	543.39 *	3
12	2.35 ± 0.33	13.87 ^{ns}	11	2.0×10^5 *	12	2.0×10^{15} *	12

^{ns} Not significant. * Significant at the 5% probability level. df = degrees of freedom.

3.4. Number of Samples from the Sampling Plan with the Beating Tray Technique

The regression curve of the common aggregation parameter of the negative binomial frequency distribution (*Kcommon*) of the 12 soybean crops as a function of the individual k parameter in each field showed a significant slope ($p < 0.05$) and a non-significant intercept ($p > 0.05$) (Table 2). Therefore, there was a common parameter ($kc = 0.3787$) for the negative binomial frequency distribution of caterpillar densities in soybean fields evaluated with the beating tray technique.

Table 2. Analysis of variance of caterpillar densities per sample determined by sampling with the beating tray technique in 12 soybean crops, carried out to verify the existence of a common aggregation parameter (kc) in a negative binomial distribution.

Variance Source	df	Sum of Squares	Mean Squares	F
Slope 1/kc	1	49.84	49.84	13.73 *
Intercept	1	1.51	1.51	0.42 ^{ns}
Error	9	32.67	3.63	
$Kc = 0.3787$				

* Significant at the 5% probability level. ^{ns} Not significant. df = degrees of freedom.

It was found that the lowest value for the number of samples in the sampling plan was reached when the sampling error was 25% (Figure 5). Thus, this error was used in calculating the number of samples necessary for the sampling plan. The number of samples with the beating tray technique was 61 per field, with a maximum error of 25% (Figure 5).

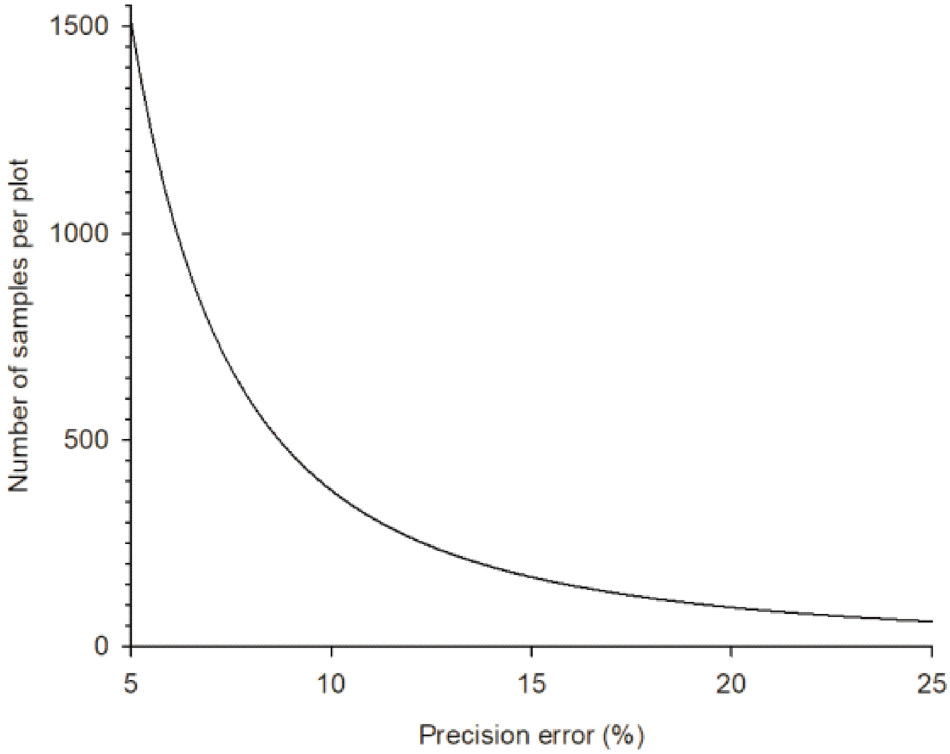

Figure 5. Number of samples as a function of the sampling error required to assess caterpillar populations in soybean fields using the beating tray technique.

3.5. Decisions, Time, Cost, and Validation of the Use of the Sampling Plan and the Control Levels Determined by This Study

The walking distance and the walking time in the 22 soybean fields evaluated were similar for the sampling plans, whether with the beating tray technique or the beating cloth technique (Figure 6 and Table 3).

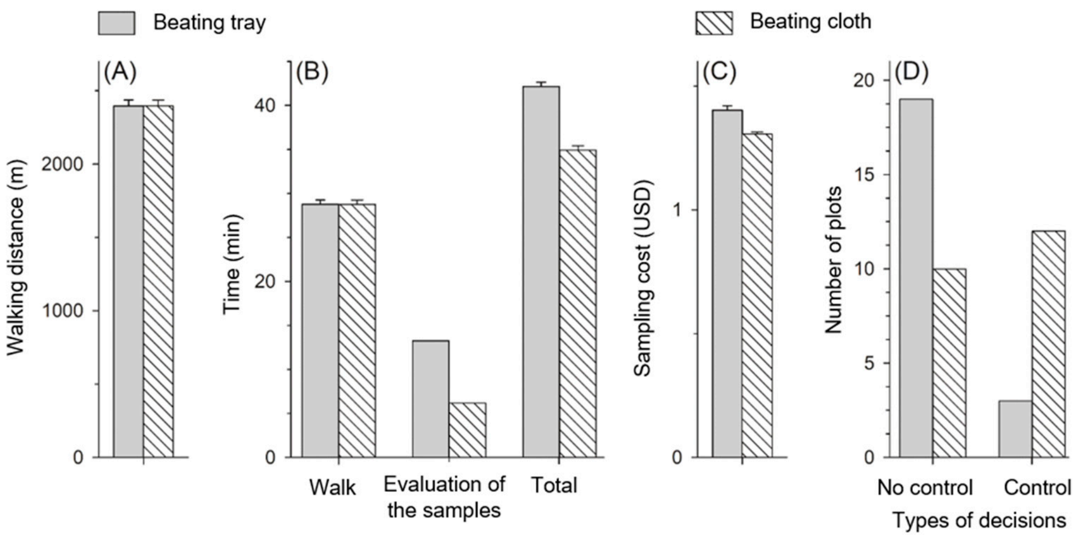

Figure 6. (**A**) Distance walked, (**B**) walking times, sample evaluation, and sampling total, (**C**) sampling cost, and (**D**) number of caterpillar control and non-control decisions by decision-making systems with a beating tray (61 samples per field) and with a beating cloth (10 samples per field) in 22 soybean fields of 20 hectares.

Table 3. Dens. = density (caterpillars/sample); Dec. = decision (Ct = control and Nc = no-control); Walk. dist. = walking distance (m); times of Walk. = walking; Eval. = sample evaluation; and total (min); cost of sampling by the decision-making systems with the beating tray technique (61 samples per field) and the beating cloth technique (10 samples per field) in 22 soybean fields of 20 hectares.

Field	Decision-Making System with Beating Tray							Decision-Making System with Beating Cloth						
	Dens.	Dec.	Walk. Dist. (m)	Time (min)			Cost (USD)	Dens.	Dec.	Walk. Dist. (m)	Time (min)			Cost (USD)
				Walk.	Eval.	Total					Walk.	Eval.	Total	
							Vegetative Stage							
1	1.02	Nc	2373.54	28.49	13.25	42.14	1.39	16.80	Ct	2373.54	28.49	6.16	34.65	1.30
2	0.16	Nc	2609.68	31.30	13.25	44.55	1.47	3.50	Nc	2609.68	31.30	6.16	37.46	1.35
3	0.36	Nc	2540.72	30.49	13.25	44.14	1.45	5.70	Nc	2540.72	30.49	6.16	36.65	1.34
4	0.26	Nc	2349.64	28.37	13.25	42.02	1.39	4.60	Nc	2349.64	28.37	6.16	34.53	1.30
5	0.07	Nc	2319.35	27.83	13.25	41.08	1.36	0.60	Nc	2319.35	27.83	6.16	33.99	1.29
6	0.20	Nc	2246.10	26.99	13.25	40.24	1.33	2.90	Nc	2246.10	26.99	6.16	33.15	1.27
							Reproductive Stage							
7	0.20	Nc	2884.08	34.61	13.25	48.26	1.58	3.50	Nc	2884.08	34.61	6.16	40.77	1.41
8	0.13	Nc	2779.99	33.35	13.25	47.00	1.54	2.30	Nc	2779.99	33.35	6.16	39.51	1.39
9	1.02	Nc	2689.02	32.26	13.25	45.51	1.50	18.00	Ct	2689.02	32.26	6.16	38.42	1.37
10	0.20	Nc	2481.08	29.83	13.25	43.08	1.42	3.20	Nc	2481.08	29.83	6.16	35.99	1.32
11	0.41	Nc	2429.86	29.07	13.25	42.32	1.40	7.20	Ct	2429.86	29.07	6.16	35.23	1.31
12	4.64	Ct	2386.28	28.75	13.25	42.00	1.39	34.70	Ct	2386.28	28.75	6.16	34.91	1.31
13	0.38	Nc	2294.88	27.50	13.25	41.15	1.36	5.70	Ct	2294.88	27.50	6.16	33.66	1.28
14	1.18	Nc	2275.73	27.26	13.25	40.51	1.34	19.40	Ct	2275.73	27.26	6.16	33.42	1.28
15	0.33	Nc	2261.47	27.09	13.25	40.34	1.33	5.50	Ct	2261.47	27.09	6.16	33.25	1.28
16	0.64	Nc	2251.71	27.03	13.25	40.28	1.33	11.70	Ct	2251.71	27.03	6.16	33.19	1.28
17	0.59	Nc	2244.30	26.96	13.25	40.21	1.33	10.90	Ct	2244.30	26.96	6.16	33.12	1.27
18	1.31	Nc	2246.01	27.01	13.25	40.26	1.33	23.70	Ct	2246.01	27.01	6.16	33.17	1.27
19	0.64	Nc	2250.95	26.97	13.25	40.22	1.33	11.10	Ct	2250.95	26.97	6.16	33.13	1.27
20	1.30	Nc	2258.87	27.10	13.25	40.35	1.33	23.10	Ct	2258.87	27.10	6.16	33.26	1.28
21	4.25	Ct	2269.54	27.19	13.25	40.44	1.39	34.90	Ct	2269.54	27.19	6.16	33.35	1.28
22	3.72	Ct	2282.73	27.40	13.25	41.05	1.58	33.00	Ct	2282.73	27.40	6.16	33.56	1.28

The evaluation time, the total time, and the sampling cost varied according to the sampling plan. The average time and total cost of sampling for the beating tray technique were 42.14 min and USD 1.40, respectively, per 20 ha field (to evaluate 61 samples). The average time and total cost of sampling for the beating cloth were 34.93 min and USD 1.31, respectively, per 20 ha field (to evaluate 10 samples) (Figure 6 and Table 3).

The decision-making system with the beating tray technique indicated a decision not to control the caterpillars in all six soybean fields in the vegetative stage. Meanwhile, the decision-making system with the beating cloth technique indicated control and non-control decisions in one and five soybean fields in the vegetative stage, respectively (Table 3).

In soybean fields in the reproductive stage, the decision-making system with the beating tray technique indicated control decisions in three fields and no-control decisions in thirteen fields. Meanwhile, the decision-making system with the beating cloth technique indicated control decisions in thirteen fields and non-control decisions in three fields (Table 3).

4. Discussion

The Lepidoptera species observed (*A. gemmatalis*, *C. includens*, *H. armigera*, *S. cosmioides*, *S. eridania*, and *S. frugiperda*) are the main pests in soybean fields worldwide [12,14]. These species are polyphagous and have a wide geographic distribution worldwide [7,14]. Climatic conditions, food supply (due to planting succession and the occurrence of spontaneous plants), and the ability of these insects to disperse favor the increase in their populations [7,30]. Furthermore, caterpillars of the genus *Spodoptera* mainly attack pods and grains [12,17]. This occurred in soybean fields since the highest density of *S. cosmioides* caterpillars occurred when the plants were in the reproductive stage.

The sampling techniques used to monitor insect pests on crops must be simple, accurate, representative, and efficient [27,29]. Despite having detected significant densities of caterpillars in soybean fields by all the sampling techniques used in this study, data analysis revealed they had very different efficiencies. A beating tray was the best technique for sampling caterpillars, as it showed adequate accuracy (with a relative variance lower than 25%) and a shorter sampling time in all phenological stages of the soybean plants. Sampling techniques that assess pest densities with a relative variance below 25% are more accurate and representative [16,29]. In addition, the technique that has a shorter sampling time favors the generation of low-cost sampling plans and, therefore, is practicable [16,29]. Although the beating cloth and direct counting techniques are the most used in soybean crops [7,12,16], they are not the most accurate and present higher execution times and costs than the beating tray technique.

The decision-making indices used in IPM programs must be sturdy, accurate, and representative [6,8]. The economic thresholds determined in this study (7.11 and 3.60 caterpillars per tray in fields with plants in the vegetative and reproductive stages, respectively) have those characteristics. They are sturdy because the curve used for these determinations has a high degree of significance ($p < 0.0001$) [31]. They are accurate because these curves have high predictability ($R^2 = 0.94$) for the variables involved [32]. Meanwhile, they are representative because these indices were determined in commercial soybean fields, representing the reality of these phenomena [24].

In the past, frequency distributions were thought to be related to the spatial distribution of pests in fields [3,33,34]. With the evolution of geostatistical analyses, it is now possible to determine the spatial distribution of pests in fields [35]. Studies using geostatistics have shown no relationship between the spatial distribution of pests in crops and the frequency distribution of their density data [35,36]. Determining the frequency distribution of pest density data makes it possible to select the most appropriate formula for the calculation of the number of samples in the sampling plans [3,27–29]. This procedure was carried out in this study. Hence, the observed frequency densities of caterpillars fit the negative binomial distribution. Therefore, the formula for calculating the number of samples in the sampling plan should be that of data following the negative binomial frequency distribution [28]. The data that fit the negative binomial frequency distribution are characterized by presenting variance greater than the average [3,27,28], a fact that was verified in this study with the densities of caterpillars in soybean fields.

Given the above results, the sampling plan determined in this work will be suitable for evaluating the populations of caterpillars in different soybean fields. In addition, those fields had plants at different phenological growth stages, which indicates that the sampling plan generated in this study can be applied in the evaluation of soybean fields from start to finish [16,29].

The fact that the two sampling techniques (beating tray and beating cloth) featured different decisions (control or not) in 50% of soybean fields indicates that some of the decisions made were incorrect. As the beating tray technique used in the decision-making systems presented adequate accuracy in all soybean phenological stages (RV < 25%), this error can be related to the number of samples in the sampling plan currently used (beating cloth). The number of samples in a sampling plan should enable a reliable pest density to be determined. The number of samples must be associated with the tolerated error (maximum 25%) [25,29,37]. This prerequisite was used to determine the number of samples in the sampling plan using the beating tray technique as determined in this study. Meanwhile, using the formula for calculating the number of samples [25,27,38] for data that follow the negative binomial frequency distribution and the parameters determined in this study, it was found that the beating cloth sampling plan with 10 samples in fields of 20 hectares had a maximum error of 61.50% associated with the determination of their densities.

As the sampling plan needed for the beating tray technique has a greater number of samples (61 samples) than the plan with the beating cloth technique (10 samples), it could be expected that these two plans would have different execution times and costs. However, it was found that this did not occur since, in sampling a field of 20 hectares of soybean, the plan in the beating tray technique had an execution time and cost of only 7.21 min and USD 0.09 more. This is because most of the time was spent walking the field (68.56 to 82.36%). The walking time does not vary depending on the number of samples, since, for sampling, it is necessary to go through the entire field for the sample's evaluation [5,24]. Beyond that, the time and cost of a sample using the beating cloth technique are greater than those of a beating tray.

5. Conclusions

In conclusion, the decision-making system for controlling caterpillars determined in this work can be incorporated into IPM programs in soybean fields because it is accurate, representative, practicable, fast-acting, and low-cost. This system comprises a sampling plan and an economic threshold of 7.11 caterpillars/sample and 3.60 caterpillars/sample (for plants in the vegetative and reproductive stages, respectively). In this sampling plan, the area must be divided into up to 20 ha plots. Sixty-one plants must be beaten on a white plastic tray in each field. Furthermore, the plants must be distributed throughout the soybean field area, and the number of caterpillars present at the bottom of the tray must be evaluated. The sampling plan is low-cost (up to USD 1.40 per sampling), quick (up to 42 min), and can be used in the different phenological stages of soybean plants.

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