UNIVERSIDADE FEDERAL DE VIÇOSA

DANIEL VICTOR CHAVES NEVES

DECISION-MAKING SYSTEMS FOR THRIPS CONTROL IN SOYBEAN CROPS USING TRACTOR AND AIRCRAFT INSECTICIDE APPLICATIONS

VIÇOSA - MINAS GERAIS
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Advisor: Marcelo Coutinho Picanço

Co-advisor: Mayara Cristina Lopes

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

T

N518d
2021

Neves, Daniel Victor Chaves, 1993-
Decision-making systems for thrips control in soybeancrops using tractor and aircraft insecticide applications / Daniel Victor Chaves Neves. - Viçosa, MG, 2021.
31 f. : il. (algumas color.) ; 29 cm.

Texto em inglês.
Orientador: Marcelo Coutinho Picanço.
Dissertação (mestrado) - Universidade Federal de Viçosa.
Referências bibliográficas: f. 28-31.

1. Thripidae - Controle. 2. *Glycine max* - Doenças e pragas - Aspectos econômicos. 3. Amostragem. I. Universidade Federal de Viçosa. Departamento de Entomologia. Programa de Pós-Graduação em Entomologia. II. Título.

CDD 22. ed. 595.758

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APPROVED: February 23, 2021.

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ACKNOWLEDGMENTS

Agradeço, primeiramente, a Deus por ter abençoado meus caminhos e ter me permitido tornar meu sonho possível.

A Universidade Federal de Viçosa e ao Programa de Pós-Graduação em Entomologia, pela oportunidade de realização deste curso.

Ao Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), a Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) - Código de Financiamento 001 e a FAPEMIG pelo financiamento dos meus estudos.

Ao professor Marcelo Coutinho Picanço pela participação na minha formação, orientação e amizade ao longo desses anos de convívio. A sua esposa Kátia e aos seus filhos Mayara, Luíza e Marcelo Filho, pelo agradável convívio.

Aos membros da banca, pela cordialidade em aceitar o convite e pela forma valiosa como participaram.

Aos amigos do Laboratório de Manejo Integrado de Pragas pelo convívio, troca de conhecimentos e especialmente pela grande ajuda neste trabalho.

Aos amigos de república, do Posinho 1622, da Entomologia, do Instituto e de todos aqueles lugares pelos quais eu passei, pelo apoio, incentivo e por todos momentos felizes compartilhados.

A Laiza, pelo amor, companheirismo, amizade, incentivo e paciência demostrada ao longo de nossa convivência.

Aos meus irmãos Diêgo, Débora, Dayane, Eduardo e Maria, pela amizade e torcida.

Aos meus tios, tias e familiares, por todo apoio durante minha caminhada.

Aos meus avós, Gesulino, Maria e Izabel, pelo incentivo e carinho.

Em especial, agradeço aos meus pais Edvaldo e Joaquina, pelo amor incondicional, ensinamentos e dedicação desde o meu primeiro dia de vida.

Muito obrigado!

BIOGRAPHY

DANIEL VICTOR CHAVES NEVES, filho de Edvaldo José Neves e Joaquina Chaves da Conceição, nasceu em Janaúba, Minas Gerais, no dia 13 de janeiro de 1993. Em março de 2010, ingressou no curso de Técnico em Agropecuária integrado ao ensino médio no Instituto Federal do Norte de Minas Gerais - Campus Januária e finalizou em 2012. Em maio de 2013, ingressou no curso de Agronomia da Universidade Federal de Viçosa e graduou-se em janeiro de 2019. Durante toda a graduação, foi estagiário no Laboratório de Manejo Integrado de Pragas do Departamento de Entomologia da Universidade Federal de Viçosa, sob orientação do Professor Marcelo Coutinho Picanço. Morou um ano no exterior realizando intercâmbio na empresa Intergrow Greenhouses Inc. Em março de 2019 ingressou no curso de mestrado do Programa de Pós-Graduação em Entomologia/UFV.

“Feliz aquele que transfere o que sabe e *aprende o que ensina!”*

Cora Coralina

ABSTRACT

NEVES, Daniel Victor Chaves, M.Sc., Universidade Federal de Viçosa, February, 2021. **Decision-making systems for thrips control in soybean crops using tractor and aircraft insecticide applications**. Advisor: Marcelo Coutinho Picanço. Co-advisor: Mayara Cristina Lopes.

Soybean, *Glycine max* (L.) Merrill, is the most cultivated legume in the world. In recent years, thrips (Thysanoptera: Thripidae) have caused damage of up to 17% in these crops. The economic injury levels (EIL) and sampling plans are part of the decision-making systems of integrated pest management (IPM) programs. In sequential sampling plans, decision making is carried out after the evaluation of each sample. The EIL is the pest with the lowest density that causes economic damage, and EIL and sequential sampling plans depend on the technology used to apply the insecticides. In soybean crops, pesticides are applied mainly by tractors or airplanes. To date, there are no decision-making systems for thrips in soybean crops. Thus, the objective of this work was to develop control decision-making systems for thrips in soybean crops. To this end, research was conducted in 60 commercial soybean fields for two years. The observed thrips were *Caliothrips phaseoli* and *Frankliniella schultzei*. The EIL were 3.43 and 4.53 thrips sample^{-1} for insecticide application using tractor and airplane, respectively. The sequential sampling plans were able to make correct decisions in any situation with a maximum of ten samples, and they showed savings of more than 87% of the samples, time, and cost in relation to the conventional sampling plan. Therefore, the control decision-making systems for the thrips determined in this work could be incorporated into IPM programs in soybean crops due to the *system's ability to* make correct and quick decisions.

Keywords: Economic injury levels. Sampling plans. *Glycine max. Caliothrips phaseoli. Frankliniella schultzei.*

RESUMO

NEVES, Daniel Victor Chaves, M.Sc., Universidade Federal de Viçosa, fevereiro de 2021. **Sistemas de tomada de decisão para o controle de tripes em lavouras de soja usando aplicações de inseticidas por trator e avião**. Orientador: Marcelo Coutinho Picanço. Coorientadora: Mayara Cristina Lopes.

A soja (Glycine max) é a leguminosa mais cultivada no mundo. Nos últimos anos os tripes (Thysanoptera: Thripidae) têm causado danos de até 17% nessas lavouras. Os níveis de dano econômico (NDE) e os planos de amostragem são partes dos sistemas de tomada de decisão dos programas de manejo integrado de pragas (MIP). Nos planos de amostragem sequencial a tomada de decisão é realizada após a avaliação de cada amostra. Já o NDE é a menor densidade da praga que causa danos econômicos. Os NDE e os planos de amostragem sequenciais dependem da tecnologia de aplicação dos inseticidas. Nas lavouras de soja os pesticidas são aplicados principalmente por trator ou avião. Até o momento, não existem sistemas de tomada de decisão para os tripes em lavouras de soja. Assim, o objetivo deste trabalho foi desenvolver sistemas de tomada de decisão de controle para os tripes em lavouras de soja. Para tanto, foram conduzidas pesquisas em 60 campos comerciais de soja durante dois anos. Os tripes observadas foram *Caliothrips phaseoli* e *Frankliniella schultzei*. Os NDE foram 3.43 e 4.53 tripes. amostra-1 para aplicação de inseticidas usando trator e avião. Os planos de amostragem sequencial foram capazes de tomar decisões corretas em qualquer situação com no máximo 10 amostras e eles apresentaram economia de mais de 87% das amostras, tempo e custo em relação ao plano convencional de amostragem. Portanto, os sistemas de tomada de decisão de controle para os tripes determinados neste trabalho podem ser incorporados a programas de MIP em lavouras de soja por eles tomarem decisões corretas e rápidas.

Palavras-chave: Níveis de dano econômico. Planos de amostragem. *Glycine max*. *Caliothrips phaseoli. Frankliniella schultzei*.

SUMMARY

1. Introduction

Decision-making systems are essential components of integrated pest management (IPM) programs and are composed of sampling plans and decision-making parameters (Lima et al., 2019; Moura et al., 2018; Pedigo and Rice, 2014; Pinto et al., 2017). The correct pest control decisions require simplicity, precision, quick assessment, and low cost. If evaluations of pest densities in crop fields are not carried out with adequate precision and frequency, there is a risk that decisions would be made in the wrong way, resulting in the performance of unnecessary applications or the non-use of control when necessary (Bueno et al., 2020; Paes et al., 2019; Pereira et al., 2017).

Sampling plans can be conventional or sequential (Pedigo and Rice, 2014, Lopes et al., 2019a). In conventional sampling plans, the number of samples is fixed. In sequential sampling plans, the number of samples varies according to the pest density in the crop, and the decision is taken after the evaluation of each sample (Costa et al., 2019; Paes et al., 2019). For the validation of sequential sampling plans, the conventional sampling plan was used as a comparison standard. In this process, the sequential plan is considered valid when it makes decisions similar to those of the conventional plan and with a smaller number of samples (Gusmão et al., 2006; Costa et al., 2019, Lopes et al., 2019a; Moura et al., 2018; Paes et al., 2019).

In the decision-making process, the pest density is compared with the economic injury level (EIL), which is the lowest density of the pest that causes economic damage to the crop (Higley & Pedigo, 1996). The EIL is calculated using all the pest control system components such as the cost of control, the value of crop production without the pest's attack, and the efficiency of the control method (Pedigo & Higley, 1992). The control cost is influenced by the method of applying insecticides, which can be manually, through a tractor, or through an aircraft (Bueno et al., 2020; Pedigo and Higley, 1992; Pedigo and Rice, 2014).

Soybean, *Glycine max* (L.) Merrill, is the main legume cultivated in the world, with an annual production of 361 million tons of grains and occupying an area of 125 million ha (USDA, 2019). This commodity is among the main crops grown worldwide, with different uses in human and animal nutrition. The main driver of the global demand for soy has been China's need to address changes in its population's eating habits (Giraudo, 2020). In this sense, as soybean production expands over the years, there is a growing need to control newly established insect pests in cultivated fields (Bueno et al., 2020).

Among the pests that attack soybean crops, thrips (Thysanoptera: Thripidae) are considered as emerging pests. In recent years, thrips have been gaining prominence in soybean crops because of the damage that farmers and technicians have reported (Agrocampo, 2019; Engel and Pasini, 2020). According to Gamundi and Perotti (2009), thrips are capable of causing losses of up to 17% in soybean crops. Thrips are insects that cause direct damage by sucking cellular content and injecting toxins into plants and indirect damage as a tospovirus vector (Riley et al., 2011; Paes et al., 2019). Thrips feed mainly on floral parts such as petals and pollen, resulting in stains, deformation of flower buds (abortion), and reduced fruiting (pod formation) (Childers and Bullock, 1999). For pest control in soybean crops, insecticides are applied mainly using tractors and airplanes (Cunha et al., 2017). These two application methods have different costs, speed, limitations, and potential use (Costa, 2017).

Despite the importance of soybean and thrips as pests, a decision-making system for this pest in this crop has not yet been determined. Thus, the objective of this work was to develop a decision-making system for thrips in soybean crops. To this end, research was conducted in 60 commercial soybean fields for two years to determine the economic injury levels and sequential sampling plans to apply insecticides using a tractor or an airplane.

2. Material and methods

2.1 Experimental conditions

This study was carried out during the years 2017 to 2019 in 60 commercial soybean fields in Formoso do Araguaia (11° 49' 2.80" S, 49° 39' 15.40" W, 240 m altitude) and Gurupi (11° 45' 20.90" S, 48° 51' 24.20" W, 287 m altitude) in the state of Tocantins, Brazil, wherein the climate is tropical, with dry winters and rainy summers. The variety used was M8808 IPRO (maturation group 8.8, determined growth and late cycle), and each cultivation field had about 20 ha, the spacing used was 0.45 m between rows and a density of ten plants per meter. Normal cultivation practices were conducted in the fields (Sediyama et al., 2015).

The thrips specimens observed attacking the soybean plants were collected and stored in 10-mL glass bottles with 90% ethyl alcohol solution for later identification. The specimens were identified by Professor Adriano Cavalleri from the Universidade Federal do Rio Grande, São Lourenço do Sul, Rio Grande do Sul, Brazil.

Thrip densities were evaluated using the technique of beating the apical part of the plant against a white plastic tray (40 × 25 × 3 cm). In these evaluations, *the plant’s apex was agitated inside the plastic tray,* and then the number of thrips present at the bottom of the tray was counted (Fig. 1B). This technique was used because it is the most suitable for sampling thrips in crops (Silva et al., 2019).

This work was carried out in three stages. First, the economic injury level was determined. Second, sequential sampling plans were determined. Third, the sequential sampling plans were validated.

2.2. Determination of economic injury levels

In this stage of the work, the pest control costs, the value of crop production without the pest's attack, and the economic injury levels were determined.

2.2.1 Pest control costs

In collaboration with the agricultural market, a survey was carried out on the insecticides, adjuvants, equipment, and the average number of applications used to control the thrips in soybean crops used by tractors and airplanes. The costs of controlling the thrips with the application of insecticides using a tractor and airplane were calculated because these are the main methodologies used in applying pesticides in soybean crops (Cunha et al., 2016; Cunha et al., 2017). Subsequently, a survey of the inputs (and their prices) used to control the thrips in Brazil's main soy-producing regions was carried out.

The products used in the calculations were selected using two criteria: (i) those most used by producers and (ii) the rotation of products with different modes of action, according to the principles of pest resistance management for insecticides (Lopes et al., 2019; Paes et al., 2019; Mouden et al., 2017). The control cost for thrips in the soybean crops was calculated based on these data (Pedigo and Rice, 2014; Pereira et al., 2017).

2.2.2. Estimated production value of the soybean crops without the attack of the pest

The production value of the soybean crops without the pest attack was calculated using equation (*1*):

$$V_0 = Y_0 \times Pr \qquad (1)$$

where V_0 is the production value without pest attack (US\$ ha^{-1}), Y_0 is the harvest yield without pest attack (kg · ha^{-1}), is and Pr = average soy price (US\$ kg^{-1}). The average price of soy (US\$ kg^{-1}) was determined from a survey on the average price of soy in Brazil in the recent years (CONAB, 2017). The average productivity of soybean crops in Brazil was used (FAOSTAT, 2018).

2.2.3. Determination of the loss curve in production components as a function of pest density

This stage of the work was carried out in four commercial soybean fields. Each field's area was divided into ten parts, each considered a repetition. The density of the thrips was evaluated in each repetition when the plants were in the vegetative and reproductive stages. In each repetition, ten plants were selected at random, and the percentage of the abortions of flowers was evaluated. Therefore, during the plant reproductive stage, the number of aborted flowers and the number of flowers that became pods in each repetition's ten plants were evaluated (Fig. 1A). This evaluation was carried out because abortion of some flowers of the soybean plants with thrips was observed. Furthermore, in many plant species, it has been reported that the attack of thrips causes miscarriage of flowers (Mouden et al., 2017). The flower abortion rate was calculated using the equation (2):

$$Far = (100 \times Naf) \div Tnf \qquad (2)$$

where *Far* is the abortion rate of flowers (%), *Naf* is the number of flowers aborted in the ten plants evaluated in each repetition, and *Tnf* is the total number of flowers in the ten plants evaluated in each repetition.

Data on flower abortion rates in the 40 replicates of the four cultivation fields as a function of thrips density in plants in the vegetative and reproductive stages were subjected to Pearson's correlation analysis at $P < 0.05$ (Freedman et al., 2007). The data on the flower abortion rates at the plant stage, where a significant correlation was detected, were subjected to simple linear regression analysis as a function of the thrips density at $P < 0.05$. This model was used because it is suitable for describing the loss ratio as a function of pest density (Higley and Pedigo, 1996; Pereira et al., 2017).

2.2.4. Calculation of the economic injury levels

Initially, the percentage losses caused by the thrips that correspond to the economic injury levels for insecticide application using tractors or airplanes were calculated (Pedigo et al. 1986, Higley and Pedigo 1996, Lima et al. 2019, Lopes et al. 2019). These losses were calculated using equation (*3*):

$$PLi = (Ci \times 100) \div (V_o \times k) \qquad (3)$$

where *PLi* is the percentage loss in income corresponding to the economic injury level of method i ($i = 1$, tractor; $i = 2$, airplane) of insecticide application, *Ci* is the cost of thrips control for method *i* of insecticide application (US$ per ha^{-1}), V_o is the production value without pest attack (US$ per ha^{-1}), and k is the pest control efficiency coefficient, wherein $k = 0.80$ was used due to this being the minimum efficiency required for registration of an insecticide in Brazil (Silva et al., 2011; Pereira et al., 2017; Lopes et al., 2019).

The thrips' economic injury levels were determined using the *PLi* values in the equation of losses in the production components as a function of the thrips density. In this equation, the *PLi* value corresponds to the dependent variable (Y) and the economic damage levels to the independent variable (X) (Moura et al., 2018; Lopes et al., 2019).

2.3. Determination of sequential sampling plans

The sequential sampling plan determination was based on Wald's sequential probability ratio test (SPRT) (Naranjo et al., 1997; Wald, 1945; Cocco et al., 2015). The upper and lower decision limits were calculated using equations (4) and (5) (Young and Young, 1998; Gusmão et al., 2006):

$$LB_n = h_0 + S \times n \qquad (4)$$

$$UB_n = h_1 + S \times n \qquad (5)$$

where LB_n is the lower decision limit, n is the number of sampled units, h_0 is the intercept on the axis LB_n when $n = 0$, S is the slope of the upper and lower decision limit curves, UB_n is the upper decision limit, and h_1 is the intercept on the axis UB_n when $n = 0$.

The values of h_0, h_1, and S were calculated using equations (*6*), (*7*), and (8) (Young and Young, 1998):

$$h_0 = \frac{\ln\left(\frac{\beta}{1-\alpha}\right)}{ln\left[\frac{m_1(m_{0+k})}{m_0(m_{1+k})}\right]} \qquad (6)$$

$$h_1 = \frac{\ln\left(\frac{1-\beta}{\alpha}\right)}{ln\left[\frac{m_1(m_{0+k})}{m_0(m_{1+k})}\right]} \qquad (7)$$

$$S = k\frac{\ln\left(\frac{m_{1+k}}{m_{0+k}}\right)}{ln\left[\frac{m_1(m_{0+k})}{m_0(m_{1+k})}\right]} \qquad (8)$$

where ln is *natural logarithm,* α is *type I error,* β is type II error, m_0 is the critical density of the lower limit, m_1 is the critical density of the upper limit, and k is the common aggregation parameter of the frequency of negative binomial distribution.

For α and β, the adopted values were 0.15 (Young and Young, 1998). For m_0, the value adopted was 50% of the control level (1.72 and 2.27 thrips sample^{-1} for tractor and airplane, respectively). For m_1, the value adopted were the economic injury level (3.43 and 4.53 thrips sample^{-1} for tractor and airplane, respectively). For k, the value adopted was 1.8429 (Santos et al., 2020). The LB_n and UB_n curves were plotted according to the number of samples showing decision-making regions (without control, maintaining sampling, and control).

2.4. Validation of sequential sampling plans

Two methods were used to validate the sequential sampling plan. The first method was based on the operational characteristic curve (OC) and the average sample number curve (ASN) (Young and Young, 1998). The second validation method was based on comparing the sampling results obtained using the sequential and conventional plans for sampling thrips in commercial soybean fields (Gusmão et al., 2006; Santos et al., 2020).

2.4.1. Validation using the operational characteristic and average sample number curves

To determine OC and ASN, equations (9) and (10) (Young and Young, 1998; Gusmão et al., 2006) were used:

$$OC = \frac{\frac{(1-\beta)^{h}-1}{\alpha}}{\frac{(1-\beta)}{\alpha} - \frac{(\beta)^{h}}{1-\alpha}} \qquad (9)$$

$$ASN_n = \frac{OC_n(h_0-h_1)+h_1}{m-S} \qquad (10)$$

where m is the average number of thrips per sample, and h is the auxiliary variable dependent on m. The values of α, β, h_0, h_1, and S were determined using formulas (6), (7), and (8). A graph containing OC and ASN as a function of thrip densities was constructed for the application of insecticides using a tractor or plane. In these graphs, two vertical line segments representing critical thrip densities were inserted as m_0 and m_1.

2.4.2. Validation based on the conventional sampling plan

In the second validation method, the thrip density was evaluated in 56 commercial soybean fields. In half of these fields (28 fields), the thrip populations were sampled using the sequential sampling plan determined for the application of insecticides by tractor and the conventional sampling plan determined by Santos et al. (2020). In the other half (28 fields), the thrip populations were sampled using the sequential sampling plan determined for the application of insecticides by airplane and the conventional sampling plan determined by Santos et al. (2020). This conventional sampling plan consisted of evaluating 40 samples per field. The thrip density (mean ± standard error) assessed by the conventional plane was determined in each field. The number of samples required for decision making and the type of decision (control or non-control) for the conventional and sequential plans were also determined in each of these fields (Gusmão et al., 2006; Young and Young, 1998).

The percentage of correct decisions in the sequential plan's decision-making compared to the conventional plan (used by default) was calculated. The time savings of the sequential plane in relation to the conventional (standard) plane was calculated using equation (11) (Gusmão et al., 2006; Pereira et al., 2017):

$$Ec_j = 100 * (NA_C - NA_{Sj}) \div NA_{Sj} \qquad (11)$$

where Ec_j is the time savings with the use of the sequential sampling plan in the field j (%), j is the field (1–28), NA_C is the number of samples from the conventional plan (40 samples), and NA_{Sj} is the number of samples from the sequential plan to make a decision in field j.

From these data, the average percentage of time savings using the sequential sampling plan was calculated for the fields using each of the two application methods (tractor and plane) (Gusmão et al., 2006; Pereira et al., 2017).

3. Results

The thrip species observed attacking the soybean plants in the cultivated fields were *Caliothrips phaseoli* (Hood) and *Frankliniella schultzei* (Trybom) (Thysanoptera: Thripidae).

3.1 Economic injury levels of thrips in soybean crops

3.1.1 Cost for the control of thrips on soybean crops

The total costs of controlling the thrips in the soybean fields were US$ 9.03 or 13.09 ha^{-1} for the application of insecticides using tractors or airplanes, respectively. Of these total costs, 56% and 38% were spent on insecticides, 40% and 59% were spent on equipment and services, and 4% and 3% were spent on adjuvants for pest control with the application of insecticides using a tractor or airplane, respectively (Table 1).

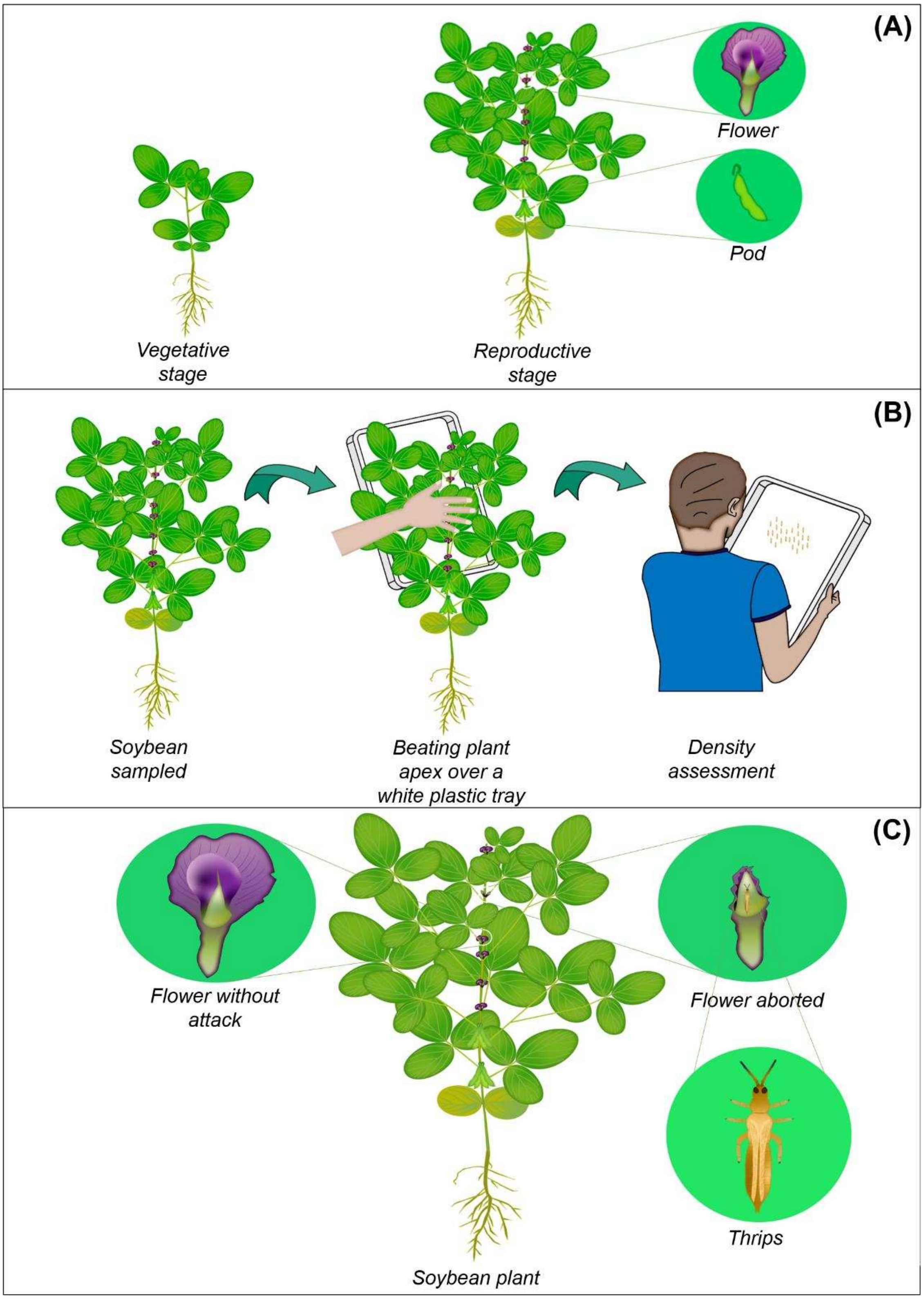

Fig. 1. (A) Phenological stages of soybean plants, (B) sampling the density of thrips using a plastic tray, and (C) assessing losses due to flower abortion.

Table 1. Cost of insecticides, adjuvant, equipment and services used to control spraying thrips using tractor or airplane

Inputs	Chemical group	Unit	U.C (US$)	Quantity (ha^{-1})	S.C (US$ ha^{-1})
Insecticides:					
Acephate 750 SP	Organophosphate	kg	10.31	0.500	5.16
Cypermethrin 250 EC	Pyrethroid	L	6.90	0.200	1.38
Clorfenapir 240 SC	Analog pyrazole	L	31.32	0.250	7.83
Espinetoram 120 SC	Spinosyn	L	128.30	0.075	9.62
Methomyl 215 SL	Oxime methylcarbamate	L	6.07	0.400	2.43
Acetamiprid 200 SP	Neonicotinoid	kg	17.02	0.250	4.25
Imidacloprid 700 WG	Neonicotinoid	kg	23.96	0.100	2.40
Thiamethoxan 250 WG	Neonicotinoid	kg	28.30	0.250	7.08
(1.1) Insecticide average cost per application (US$)					5.02
Adjuvant:					
(1.2) Spreader-sticker 200 SL		L	4.15	0.09	0.37
(1) Insecticide + Adjuvant (1.1 + 1.2)					5.39
Cost of insecticide application by tractor (equipment and services)					
PPE*			19.12	0.008^{a}	0.15
Tractor spray**			ha	1.00^{b}	3.49
(4) Subtotal					3.64
(4.1) Cost of one spray (1) + (4)					9.03
Cost of insecticide application by aircraft (equipment and services)					
PPE*			19.12	0.008^{a}	0.15
Aircraft Spray***			ha	1.00^{b}	7.55
(5) Subtotal					7.70
(5.1) Cost of one spray (1) + (5)					13.09

U.C= unit cost in US dollar. S.C= Spray cost (US$ ha^{-1}).

-* The personal protective equipment (PPE) consisted of a respirator, protective eyewear, long pants, rubber boots, and chemical-resistant suit, gloves, and apron.

-** Operational cost of tractor + bar sprayer + labor + social charges.

-*** Operational cost of aircraft + bar sprayer + labor + social charges

- ^{a} Value obtained according to the durability of the PPE.

-^{b} Value obtained according to spray efficiency.

3.1.2 Losses in plant production components as a function of thrip density

In the soybean fields, the nymphs and adults of the thrips were observed attacking new leaves and flowers of the soybean plants. The attacked leaves had clear scores due to the suction of the contents of their cells. On the other hand, in the attacked flowers, the insects were found feeding on the pollen grains, and many of these flowers aborted fallen on the ground.

The thrip densities in plants in the reproductive stage had a significant correlation ($P < 0.05$) with the rate of flower abortion in the soybean fields. In these fields, the density of thrips in plants in the vegetative stage did not show a significant correlation ($P > 0.05$) with the rate of flower abortion (Fig. 2A). The curve model used to describe the losses due to flower abortion as a function of thrip density in soybean plants in the reproductive stage was the simple linear model. It was found that the higher the thrip density in soybean plants in the reproductive stage, the greater the abortion of the flowers (Fig. 2B).

3.1.3 Determination of economic injury levels

The average yield of commercial soybean fields in Brazil in the last harvest with available data was 3,390 kg ha^{-1} (FAOSTAT, 2018). The average price received by producers of soybeans was US$ 0.33 kg^{-1} (CONAB, 2017). Using these data, the average production value of commercial soybean fields was US$ 1,121.79 ha^{-1} (Table 2).

In commercial fields with insecticide application using a tractor, the economic injury level was reached when the thrips caused 1.01% of losses in soybean yield. In the fields applied with insecticides using aircraft, the economic injury level was reached when the thrips caused 1.46% of soybean yield losses (Table 3). Applying these percentage losses to the loss curve as a function of the thrips densities (Fig. 2B), the pest's economic injury levels were 3.43 and 4.53 thrips sample^{-1} using the beating plant apex over a white plastic tray technique (Table 3).

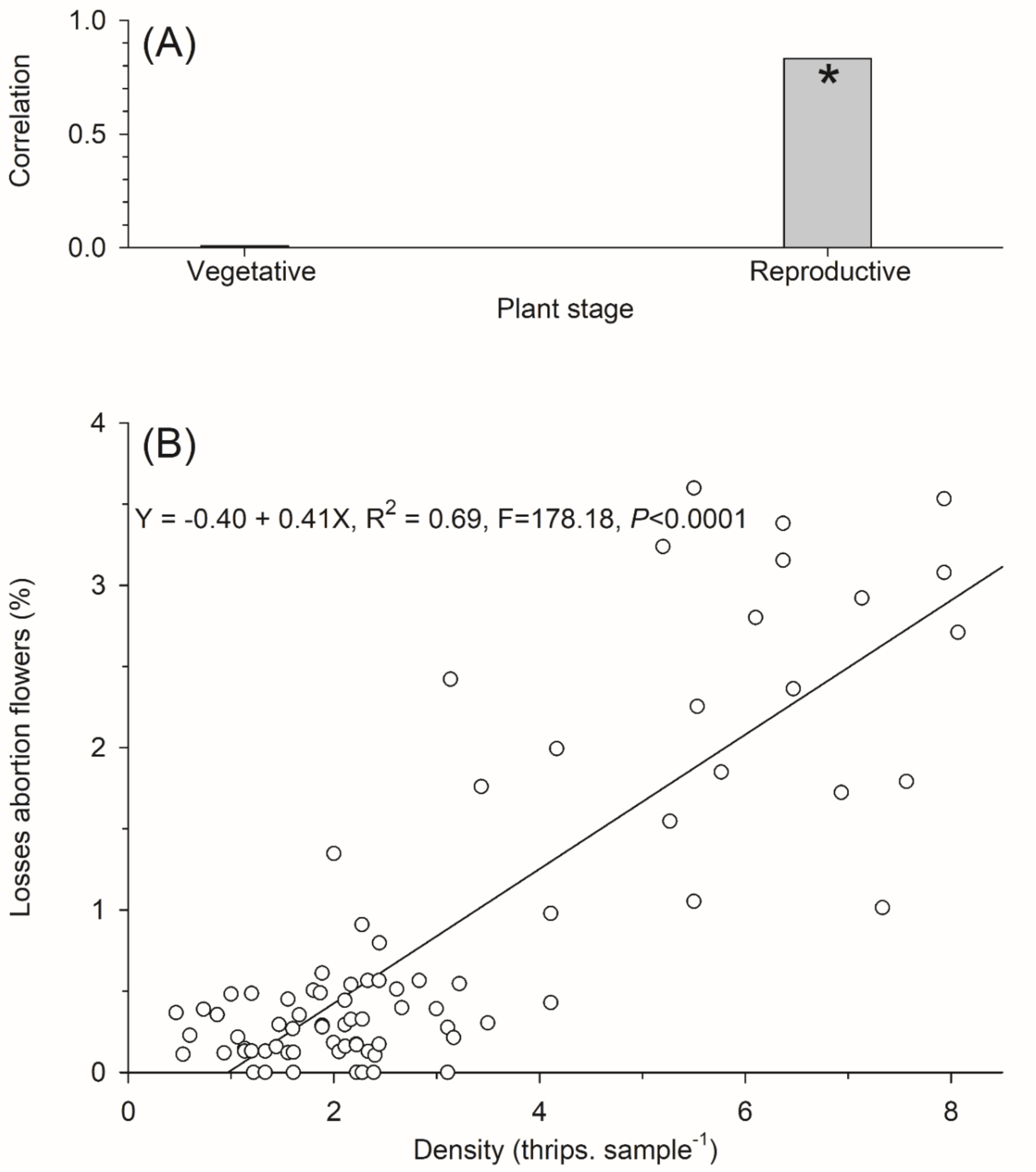

Fig. 2. (A) Correlations of thrips density (thrips. sample^{-1}) with flower abortion (%) in soybean plants in the vegetative and reproductive stages. * Significant correlations according to the z test (P < 0.05); (B) losses in yield (%) due to flower abortion due to the density of thrips in soybean plants in the reproductive stage. Each circle represents the data for one of the 80 repetitions.

Table 2. Yield and average production value in soybean crops in Brazil

Characteristics of soybean crops *	Amount
Yield (kg. ha^{-1})	3390
Average price (US$. kg^{-1})	0.33
Production value (US$. ha^{-1})	1121.79

* These values were obtained by multiplying average productivity (3390 kg. ha^{-1}) of soybean crops in Brazil based on the average price (0.33 US $. Kg^{-1}) received by producers (Quotation of the dollar R$ 5.30).

Table 3. Economic injury levels to thrips in soybean crops according to the method of application of insecticides

Application method of insecticides	Economic injury level	
	Losses (%)*	Thrips. $sample^{-1}$**
Tractor	1.01	3.43
Airplane	1.46	4.53

* Values were obtained by the equation EIL (%) = (100 × cost of control) / (0.8 × value of production without *pest's* attack).

** Values were obtained by the yield loss curve (%) in the equation contained in Fig. 2B.

3.2 Sequential sampling plans

3.2.1 Decision-making limits for sequential sampling plans

The lower (m_0) and upper (m_1) limits of the sequential sampling plan for applying insecticides with a tractor were 1.72 and 3.43 thrips sample^{-1}, respectively (Fig. 3A). For the application of insecticides by plane, the m_0 and m_1 were 2.27 and 4.53 thrips sample^{-1}, respectively (Fig. 3B).

The slope (S), lower intercept (h_1), and upper intercept (h_2) of the sequential sampling plan for application of insecticides using a tractor were 2.42, -5.79, and 5.79, respectively (Fig. 3A). As for the application of insecticides by plane, the S, h_1, and h_2 of the sequential sampling plane were 3.19, -6.83, and 6.83, respectively (Fig. 3B). At least two samples were required for the sequential sampling plans to make decisions about whether to control or not the thrips in the soybean fields (Fig. 3).

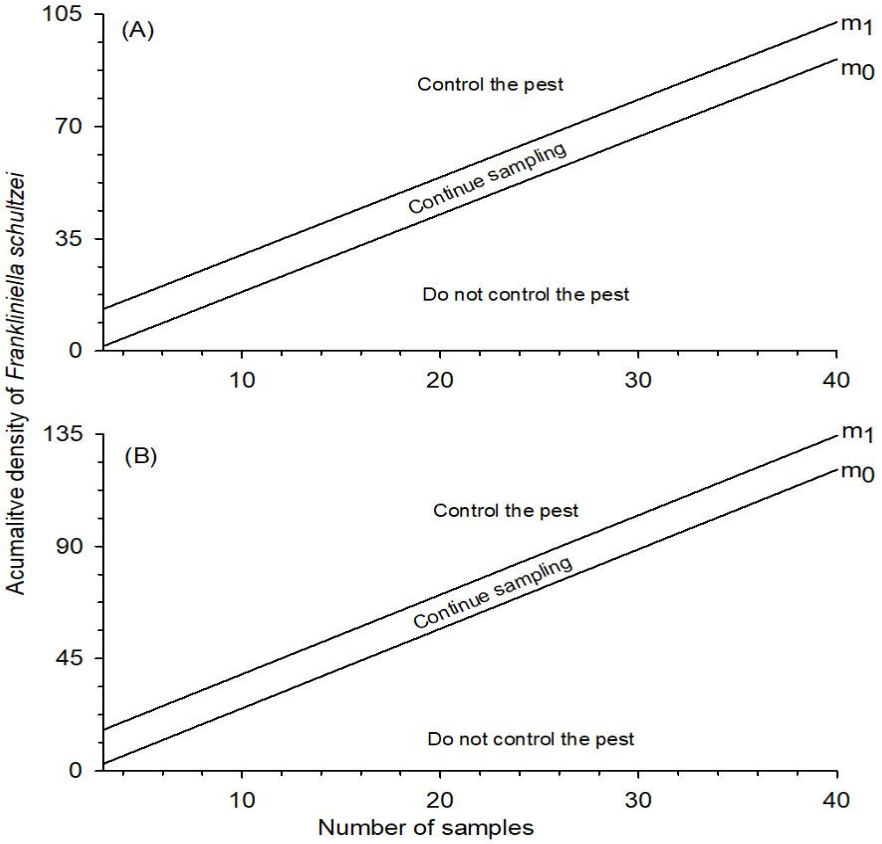

Fig. 3. Decision limits for sequential sampling plans determined for thrips in soybean crops using insecticide application through a (A) tractor or (B) airplane.

3.2.2 Validation of sequential sampling plans

According to the operational curves, the probability of not controlling the pest was 90% when its density was lower than the lower decision-making limit (m_0). The probability of not controlling the pest was 10% when its density was equal to the economic injury level (m_1) (Fig. 4). Examining the curves of the number of samples, it appears that with a maximum of ten or nine samples, decisions are made when using the sequential plans for the application of insecticides using a tractor or airplane to control the thrips, respectively (Fig. 4). All the soybean fields evaluated the conventional plan (100%), and the sequential one for application of insecticides using tractors or airplanes made the same decisions (control or non-control). In addition, the use of sequential plans for applying insecticides by tractor or aircraft saved 87.68% and 89.73% of the number of samples and sampling time, respectively, compared to the conventional plan (Tables 4 and 5).

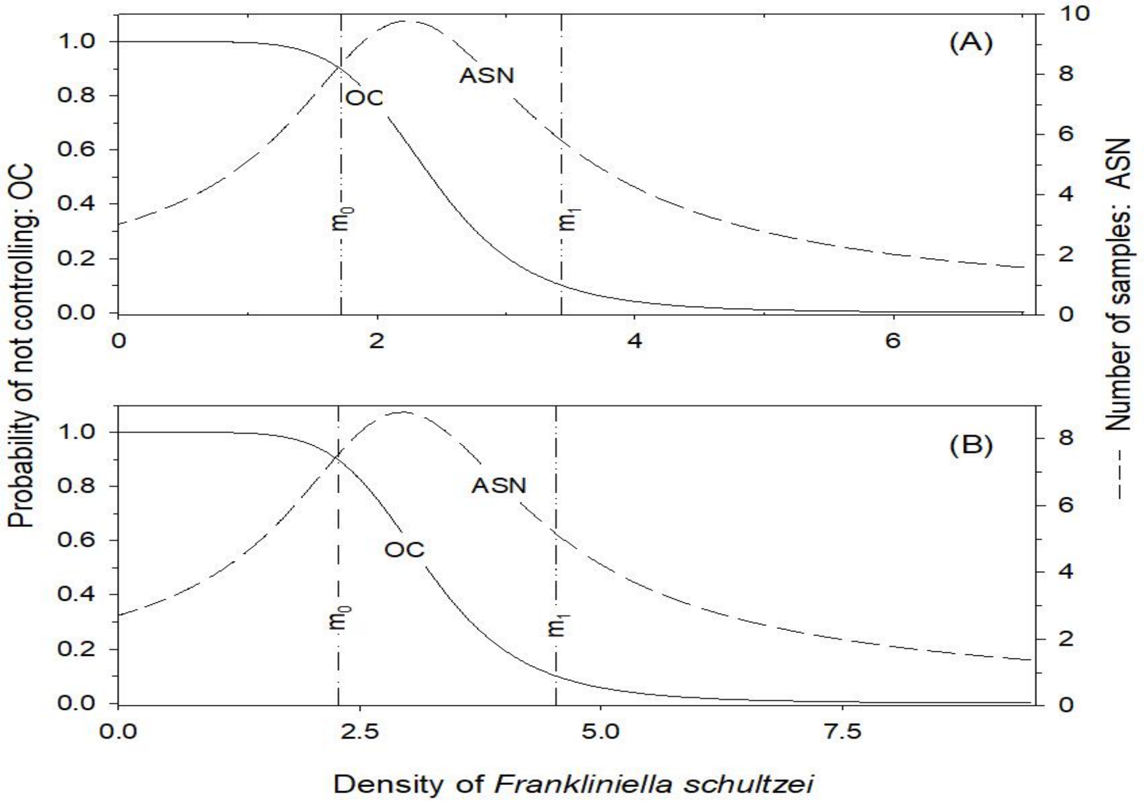

Fig. 4. Validation of sampling plans for thrips in soybean crops using the operational curve (CO) and average samples number (ASN) as a function of pest density, for application of insecticide through a (A) tractor and (B) airplane.

Table 4. Thrips density (thrips. sample^{-1}), number of samples using the sequential sampling plan, decision and time savings when adopting the sequential sampling plan compared to the conventional sampling plan (40 samples per field) in 28 commercial soybean fields with insecticide application using a tractor.

Field	Densities	Number of samples	Decision		Economy (%)
			Conventional	Sequential	
1	1.03	3	No-control	No-control	92.50
2	1.43	7	No-control	No-control	82.50
3	1.05	3	No-control	No-control	92.50
4	1.80	5	No-control	No-control	87.50
5	0.65	4	No-control	No-control	90.00
6	0.08	3	No-control	No-control	92.50
7	0.43	4	No-control	No-control	90.00
8	0.55	3	No-control	No-control	92.50
9	0.58	3	No-control	No-control	92.50
10	6.30	3	Control	Control	92.50
11	4.98	8	Control	Control	80.00
12	5.25	8	Control	Control	80.00
13	4.13	3	Control	Control	92.50
14	0.15	3	No-control	No-control	92.50
15	0.38	3	No-control	No-control	92.50
16	1.40	14	No-control	No-control	65.00
17	1.10	3	No-control	No-control	92.50
18	1.35	6	No-control	No-control	85.00
19	2.15	10	No-control	No-control	75.00
20	2.58	3	No-control	No-control	92.50
21	5.58	6	Control	Control	85.00
22	11.98	3	Control	Control	92.50
23	5.03	3	Control	Control	92.50
24	11.03	3	Control	Control	92.50
24	2.15	13	No-control	No-control	67.50
26	0.63	5	No-control	No-control	87.50
27	0.23	3	No-control	No-control	92.50
28	0.58	3	No-control	No-control	92.50

Hit 100% of the decisions and average savings of 87.68% in time adopting the sequential sampling plan compared to the conventional plan.

Table 5. Thrips density (thrips. sample^{-1}), number of samples using the sequential sampling plan, decision and time savings when adopting the sequential sampling plan compared to the conventional sampling plan (40 samples per field) in 28 commercial soybean fields with insecticide application using airplane.

Field	Densities	Number of samples	Decision		Economy (%)
			Conventional	Sequential	
29	1.58	7	No-control	No-control	82.50
30	3.18	5	No-control	No-control	87.50
31	2.88	5	No-control	No-control	87.50
32	7.43	7	Control	Control	82.50
33	11.33	3	Control	Control	92.50
34	7.35	3	Control	Control	92.50
35	9.55	3	Control	Control	92.50
36	7.60	3	Control	Control	92.50
37	6.33	4	Control	Control	90.00
38	6.53	4	Control	Control	90.00
39	8.78	7	Control	Control	82.50
40	6.93	4	Control	Control	90.00
41	5.35	3	Control	Control	92.50
42	6.38	4	Control	Control	90.00
43	4.93	4	Control	Control	90.00
44	0.50	3	No-control	No-control	92.50
45	1.33	3	No-control	No-control	92.50
46	0.60	3	No-control	No-control	92.50
47	0.80	3	No-control	No-control	92.50
48	0.18	3	No-control	No-control	92.50
49	0.10	3	No-control	No-control	92.50
50	0.03	3	No-control	No-control	92.50
51	0.03	3	No-control	No-control	92.50
52	1.48	3	No-control	No-control	92.50
53	1.13	7	No-control	No-control	82.50
54	0.58	6	No-control	No-control	85.00
55	1.58	4	No-control	No-control	90.00
56	0.88	5	No-control	No-control	87.50

Hit 100% of the decisions and average savings of 89.73% in time adopting the sequential sampling plan compared to the conventional plan.

4. Discussion

Observing the impact of thrips on soybean production components only when they attacked plants in the reproductive stage indicates that it was in this stage of the plants that they caused damage. In this context, it was observed that for every 3.44 thrips per sample (evaluated by beating the *plant's apex* in a white plastic tray), 1% of flowers were aborted in the soybean plants (Fig. 2B). Thus, the thrips *C. phaseoli* and *F. schultzei* (species observed in the soybean plants) at densities of up to eight thrips sample^{-1} (observed densities) caused damage to soybean plants by aborting flowers. In addition, it was observed that in the flowers attacked by the thrips, the pollen grains formed clusters, and the flowers aborted. Thrips have a higher fertility rate, faster development, and longer life expectancy when their females feed on pollen grains (Hulshof and Vanninen, 2002).

The cost of insecticide applications when using a tractor (US$ 9.03 ha^{-1}) is lower than when using an airplane (US$ 13.09 ha^{-1}), indicating that under normal conditions, the control of thrips in the fields of soybeans must be made using a tractor. However, in large areas and when the tractor is unable to enter the site due to the soil being soaked or the enormous plants, it is appropriate to use an airplane (Costa, 2017; Sediyama et al., 2015). In addition, when there is a need for urgent applications due to the risk of pests causing economic damage, it is appropriate to use applications using an aircraft because of its speed (0.167 min ha^{-1}) (Matthews, 2014).

In this work, economic injury levels for thrips in soybean crops were determined for the first time. The fact that these economic injury levels have been determined for the application of insecticides using a tractor and airplane is essential because these are the two most used methods in soybean crops for the application of pesticides (Cunha et al., 2017). Besides, these economic injury levels were determined in commercial cultivation fields, representing the reality of soybean crops.

In integrated pest management programs, a decision should be made to control the thrips when their density is equal to or greater than the economic injury level. Thus, it is possible to carry out pest control before it causes economic damage (Moura et al., 2018). On the other hand, when the density of thrips is less than the economic damage level, the decision is not taken into consideration

(Pereira et al., 2017). This avoids unnecessary insecticide applications, which reduces the cost of production and the impact of these pesticides on non-target organisms such as natural enemies and pollinators (Paes et al., 2019; Picanço et al., 2007)

The economic injury level for insecticide spraying using a tractor (3.43 thrips sample^{-1}) was lower than when using an airplane (4.53 thrips sample^{-1}), owing to the lower cost of controlling tractor applications. In addition, the fact that these economic injury levels differ has consequences for integrated pest management programs in soybean crops. In this context, in the first soybean fields where the first outbreaks of high populations of thrips appear, insecticides should be applied using a tractor. This must be done because the densities of this pest first reach the economic injury level for application of insecticides by tractors and because of the lower cost of these applications. (Costa et al., 2017; Matthews, 1998). In large cultivation areas with flat topography, as soybean plants occupy the entire cultivation space, the most appropriate is insecticide application using an airplane. This is due to the difficulties of moving machinery in cultivation in this situation and the need for rapid pest control (Costa, 2017; Matthews, 2014).

The fact that the sequential sampling plans determined in this work have lower and upper limits for any density of the thrips makes these plans capable of making a decision (of control or not) in any density of the pest (Young and Young, 1998; Pereira et al., 2017). Another advantage of these sequential plans is making correct (control or not), quick, and low-cost decisions. These advantages could be demonstrated by observing the operational curves that indicate a high probability (> 90%) of making correct decisions whether to control the thrips in the soybean fields or not. This correct decision-making could also be verified through validation by sampling in the commercial fields of soy cultivation since in 100% of the soy fields using insecticide the application is by tractor or airplane. The speed of the sequential sampling plans can be demonstrated by observing the curves of the number of samples needed to make a decision with up to ten samples per evaluated cultivation field. In addition, in the commercial fields sampled in the validation process, there were more than 87% savings in time and cost than in the conventional plan used as a comparison standard.

5. Conclusions

The EIL and the sequential sampling plans determined in this work for the *C. phaseoli* and *F. schultzei* thrips can be incorporated into integrated pest management programs in soybean crops by making correct and quick decisions. The EILs are 3.43 and 4.53 thrips sample^{-1} for insecticide application using a tractor and airplane, respectively. These sequential sampling plans are capable of making correct decisions at any pest density with a maximum of ten samples and can save over 87% of the time and cost of sampling.

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