Research Article

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Sequential sampling plans and economic injury levels for *Empoasca kraemeri* on common bean crops at different technological levels

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Abstract

BACKGROUND: *Empoasca kraemeri* is an important pest on common bean crops at different technological levels. However, for this pest on this crop, economic injury levels have not yet been determined and plan for sequential sampling plans has not yet been developed. Thus, the objectives of this research were to develop *E. kraemeri* sequential sampling plans and to determine economic injury levels in the common bean at different crop technological levels.

RESULTS: Common bean plants tolerate low attack intensities of this pest (up to 1 adult plant^{-1}). However, with an increase in attacks, there is a reduction in grain production by the plants. The economic injury levels were 0.48, 0.39 and 0.35 adults sample^{-1} (leaf beating on a tray) for crops with low (1200 kg ha^{-1}), medium (1800 kg ha^{-1}) and high (2400 kg ha^{-1}) technological levels, respectively. Sequential sampling plans and the standardized plan produced similar decisions. However, in these decisions there was a time saving of more than 60% compared with the standardized plan.

CONCLUSION: All three economic injury levels determined and the sequential sampling plans developed in this study are suitable for incorporation into integrated management programs for common bean pests because they can be used by farmers operating at various technological levels to make adequate and rapid decisions.

Supporting information may be found in the online version of this article.

Keywords: *Empoasca kraemeri*; decision-making process; common bean; sequential sampling plan

1 INTRODUCTION

Decision-making systems are essential components of integrated pest management (IPM) programs.[1] These systems are composed of sampling plans and a decision-making index.[1,2]

In sampling plans, we evaluate the pest attack intensity on crops. Sampling plans may be standardized or sequential. In standardized sampling plans, the number of samples is fixed.[3,4] However, in sequential sampling plans, the number of samples required for the decision to apply pest control measures is variable.[2] Standardized plans are the starting point for developing the decision-making systems of IPM programs as they are used in the validation of sequential plan processes.[2,3] A valid sequential sampling plan should make decisions similar to the standardized plan; however, these decisions should be faster and less costly. In the sequential sampling plan, there are two pest control boundaries: the lower and upper boundaries. Boundary calculations depend on the decision-making index and on the frequency distribution parameters of the pest density data in the crop.[2,5]

The decision-making index used in IPM programs is the economic injury level. This index is calculated based on the control cost of the pest, the crop production value without pest attacks and the efficiency of the control method used.[2,5,6] Therefore, this decision-making index depends on a number of factors that can vary depending on the situation. Despite this variation, sequential sampling plans are developed and the economic injury level is calculated by taking fixed values (usually the mean) for these variables.[5,6]

One of the factors involved in determining the economic injury level is the crop production value.[2,5,6] One of the elements that most influence the crop production value is the technological level. In crops of a low technological level, the productivity is lower

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than in those of a high technological level.[7,8] As the production value and economic injury level are inversely proportional quantities, it is expected that the technological level will influence the pest control decision-making index as well as sequential sampling plans.[1,2,6] Despite this relationship, there are no studies dealing with this subject.

Beans are plant species of the Fabaceae family that produce grains and pods.[9] The most current data available show that the area under cultivation globally with bean species is over 65 million hectares.[10] Amongst these species, the common bean (*Phaseolus vulgaris* L.) is one of the most important economically, socially and nutritionally. Its economic importance is a consequence of the extensive cultivated area of this crop and the income from it obtained by farmers. Its social importance results from the substantial use of manpower in its cultivation and the fact that cultivation is undertaken mainly by family farmers. Its nutritional importance is a consequence of its grains and pods being rich in proteins, minerals, carbohydrates and fibers.[9]

Among the main pests that attack the common bean is the leafhopper *Empoasca kraemeri* (Hemiptera: Cicadellidae), an important pest in the tropics and subtropics.[9,11] It damages the plant through sap sucking and injection of toxins into the phloem, leading to obstruction of sap-conducting vessels and reduced productivity.[9,11–13] Despite the significance of *E. kraemeri* as a pest, there are no studies on its economic injury level and sequential sampling plans for this pest on the common bean. Thus, the objective of this research was to develop sequential sampling plans and to determine economic injury levels for *E. kraemeri* on common bean in crops of different technological levels.

2 EXPERIMENTAL METHODS

This research was divided into three steps. In the first step, we determined the economic injury level for *E. kraemeri*. In the second step, we developed sequential sampling plans for this pest. In the third step, the sequential sampling plans were validated.

2.1 Economic injury level determination

In this part of the research, we determined: the pest control cost, the regression model for plant yield (%) as a function of absolute pest density, the regression model of the density sampled by leaf beating on a tray as a function of absolute pest density, and the economic injury level.

2.1.1 Pest control cost determination

Initially, surveys were conducted with bean farmers. They were asked about the products (insecticides and adjuvants), equipment and number of applications used in *E. kraemeri* control. We conducted research into commerce in the region regarding the prices of these inputs. The products selected were those most commonly used by farmers to control this pest. Additionally, the principles of insecticide rotation with different modes of action were adopted to allow pesticide resistance management. Based on these data, we calculated the pest control cost.[2]

2.1.2 Determination of the regression model of the plant yield (%) as a function of absolute pest density

This study was conducted in a greenhouse on the Universidade Federal de Viçosa campus, Viçosa [20°48′45″ S, 42°56′15″ W, 600 m above sea level (a.s.l.); tropical climate], Minas Gerais State, Brazil. Plants were grown in 2.5-L plastic pots with each pot containing two plants. When the plants were 7 days old, they were placed in wooden cages covered by organza (3 m x 1 m x 0.8 m). Twenty-five pots were placed in each cage, with five cages being used. Each pot represented one replication. In each cage, we placed a different density of *E. kraemeri* adults. These insects were collected from common bean commercial crops. Treatments were the densities of 0.0, 0.5, 1.0, 2.0 and 4.0 *E. kraemeri* adults per plant. The cages were opened weekly for insect removal. Later the cages were closed and they were reinfested with *E. kraemeri* adults according to the treatment.

At the end of cultivation, we evaluated the plant yield. For this purpose, the pods were threshed and the grains placed into paper bags. These paper bags were placed in forced air ventilation (Marconi MA037 - MARCONI, Brazil) to dry the grains at 75 °C. This material remained in the oven until a constant weight was achieved. The grains were weighed on a precision scale with an accuracy of 0.01 g (Gehaka BK4000 - Gehaka, Brazil). The grain humidity was converted to 15% on a dry mass basis as this is the humidity content used to commercialize common bean grains.

Subsequently, we calculated the plant yield percentage for each replication using the following equation:

$$Y_i = 100 \times \left(W_i / W_0\right) \tag{1}$$

where Y_i is plant productivity (%) in the replication (i), W_i is the grain weight per plant in the replication (i) and W_0 is the grain weight average per plant in replications without pest attack.

Plant yield data (%) were subjected to regression analysis as a function of *E. kraemeri* absolute density (adults plant^{-1}). The regression model selection was based on its significance ($P < 0.05$), the higher regression coefficient (R^2) and equation simplicity.[2,14]

2.1.3 Determination of the regression model of the density sampled by leaf beating on a tray as a function of absolute pest density

This stage of the research was conducted in a greenhouse, similar to that used in the previous stage. Plants were grown in 2.5-L plastic pots and each pot contained two plants. When the plants were 30 days old, they were placed in wooden cages covered by organza (3 m x 1 m x 0.8 m). We placed 25 pots in each cage and 14 cages were used. Each pot represented a replication. In each cage, we placed a different density of *E. kraemeri* adults. The densities used were 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5 and 7.0 *E. kraemeri* adults per plant.

We sampled one plant out of 10 pots in each cage using the technique of leaf beating on a white plastic tray (45 cm x 30 cm x 5 cm). This technique was used because it is ideal for *E. kraemeri* sampling in common bean crops.[12] The selection of the pot and the plant to be sampled was randomized. For the evaluation of *E. kraemeri* density, we placed the tray at the base of the selected plant, whose leaves were vigorously shaken. We then counted the adults present in the tray. The density data (adults tray^{-1}) as a function of absolute density (adults plant^{-1}) was subjected to regression analysis at $P < 0.05$ using the criteria described in the previous section.

2.1.4 Economic injury level determination

Initially, we conducted research into the price per kilogram of common beans in 2015 and 2016. We considered farmers operating at a low, medium and high technological level to have a productivity of 1200, 1800 and 2400 kg ha^{-1}, respectively.[9] For the establishment of these three technological levels, a survey of the characteristics of and productivity obtained by Brazilian common bean farmers was

Table 1. Costs for equipment, insecticides and adjuvants used in sprays for *Empoasca kraemeri* control in common bean crops. (A) Cost of one application; (B) total cost of control

(A)

Inputs	Units	Unit cost (US$)	Quantity	Cost per application (US$)
Equipment				
Personal protective equipment[a]	ud	39.83	0.1	3.98
Tractor	h	22.15	0.1	2.22
(1) Subtotal				6.20
Insecticides				
Thiamethoxam 500 WG	kg	75.95	0.175	13.29
Carbaryl 480 SC	L	9.40	0.675	6.35
Imidacloprid 700 WG	kg	31.65	0.425	13.45
Acephate 750 SP	kg	16.75	1.050	17.59
Bifenthrin 100 EC	L	25.32	0.075	1.90
(2) Average cost of insecticide per application				10.51
Adjuvant				
(3) Sodium lauryl ether sulfate 279 SL	L	4.43	0.50	2.22
(4) Cost of one application: (1) + (2) + (3)				18.93

(B)

Cost of one application (US$)	Number of applications by crop	Total cost of control (US$)
18.93	3	56.78

[a] The personal protective equipment consisted of a respirator, chemical-resistant hat, protective eyewear, long pants, chemical-resistant suit, chemical-resistant gloves, chemical-resistant apron and rubber boots.

carried out. In this survey, it was observed that farmers operating at a higher technological level used more advanced technologies such as the no-tillage system, irrigation systems, and agronomist advised fertilization and crop rotation, and had a productivity of about 2400 kg ha^{-1}. Meanwhile, middle-level farmers used conventional technologies such as conventional tillage cultivation, fertilization without soil analysis and crop rotation only when possible, and obtained yields of around 1800 kg ha^{-1}. Farmers operating at a low technological level used simpler technologies such as minimum soil preparation, little investment in fertilization (when carried out) and family farming, and obtained yields of about 1200 kg ha^{-1}.

We calculated the economic injury level using three units: yield losses (%) ($EIL_{\%}$), absolute pest density (adults plant^{-1}) (EIL_{ad}) and sampled pest density (adults sample^{-1}) (EIL_{sp}).

In the economic injury level in terms of yield loss calculation (%), we used Eqn 2:[2,5,6]

$$EIL_{\%} = (C \times 100) / (V_0 \times K) \quad (2)$$

where $EIL_{\%}$ is the economic injury level (productivity loss percentage), C is the pest control cost (US$) (Table 1), V_0 is the production value when there is no pest attack (US$876, US$1314 and US$1752 per hectare in situations of low, medium and high technological level, respectively), and K is the pest control coefficient, for which 0.8 corresponds to 80% efficiency; the 80% level was used because this is the control efficiency used in Brazil for registering an insecticide for pest control.[2,15,16]

In order to calculate the economic injury level in terms of absolute pest density (adult plant^{-1}) (EIL_{ad}), we determined the plant yield (%) (Y_{EIL}) when the plants are subjected to pest densities equal to these indexes using Eqn 3:

$$Y_{EIL} = 100 - EIL\% \quad (3)$$

The $EIL_{\%}$ values were 8.1, 5.4 and 4.05% for low, medium and high technological level crops, respectively.

For the EIL_{ad} calculation, we added the Y_{EIL} values into the equation that described the plant yield (%) as a function of absolute pest density (adults plant^{-1}) ($Y = 100 - 0.98X^2$) (Fig. 1A). Thus, for the EIL_{ad} determination, Eqn 4 was generated:

$$EIL_{ad} = \left[\left(100 - Y_{EIL} \right) / 0.98 \right]^{0.5}. \quad (4)$$

The Y_{EIL} values used in this equation were 91.9, 94.6 and 95.95% for low, medium and high technological level crops, respectively.

In order to calculate EIL_{sp}, we added the EIL_{ad} values into the equation that described the density sampled by leaf beating on a tray as a function of absolute pest density on the plants ($Y = 0.167X$) (Fig. 1B). Thus, for EIL_{ad} determination, Eqn 5 was generated:

$$EIL_{sp} = 0.167 \times EIL_{ad}. \quad (5)$$

The EIL_{ad} values used in this equation were 2.87, 2.34 and 2.10 adults per plant for low, medium and high technological level crops, respectively.

2.2 Sequential sampling plan

2.2.1 Determination of decision-making boundaries

We developed three sequential sampling plans for *E. kraemeri* in common bean crops with low, medium and high technological

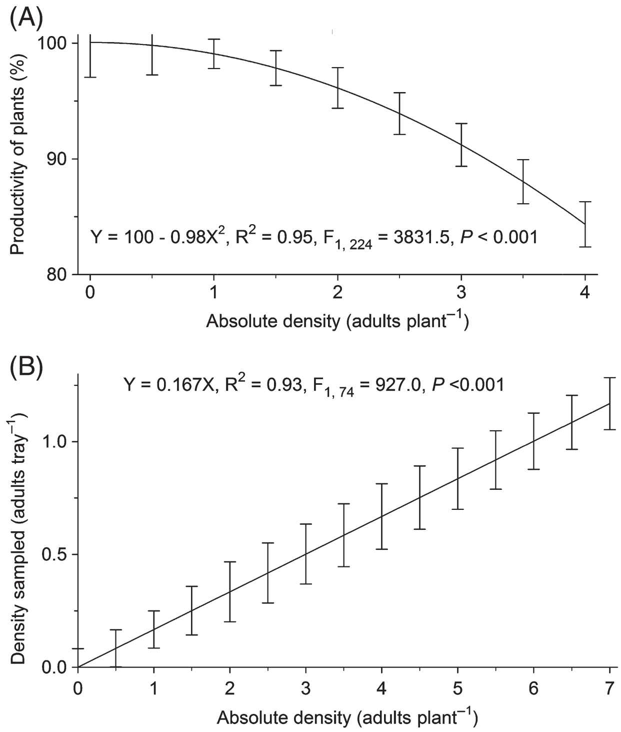

Figure 1. (A) Productivity losses in bean plants according to adult *Empoasca kraemeri* absolute density and (B) density sampled by leaf beating on a plastic tray as a function of the absolute density of the insects in the plants. The vertical lines represent the confidence curve intervals at 95% probability.

levels. The lower and upper boundaries of the sampling plans were calculated using Eqns 6 and 7:[2,5,17]

$$LB_n = h_0 + S^* n; \tag{6}$$

$$UB_n = h_1 + S^* n, \tag{7}$$

where LB_n is the lower boundary, n is the number of sampling units used (1 to 63), h_0 is the y-intercept of the curve in the lower boundary, S is the slope of the lower and upper boundaries, UB_n is the upper boundary and h_1 is the y-intercept of the curve in the upper boundary.

The values of h_0, h_1, and S were calculated using Eqns 8, 9 and 10:[2,5,17–20]

$$h_0 = \frac{\ln\left(\frac{\beta}{1-\alpha}\right)}{\ln\left[\frac{m_1(m_0+k)}{m_0(m_1+k)}\right]} \tag{8}$$

$$h_1 = \frac{\ln\left(\frac{1-\beta}{\alpha}\right)}{\ln\left[\frac{m_1\ (m_0+k)}{m_0\ (m_1+k)}\right]} \tag{9}$$

$$S = k\frac{\ln\left[\frac{m_1+k}{m_0+k}\right]}{\ln\left[\frac{m_1\ (m_0+k)}{m_0\ (m_1+k)}\right]} \tag{10}$$

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

For α and β parameters, the value of 0.10 was adopted.[5,17–19] For the m_0 parameter, the values of 50% of economic injury levels (0.24, 0.195 and 0.175) were adopted. For the m_1 parameter, the economic injury level values (0.48, 0.39 and 0.035) were adopted. For the k parameter, the value of 1.038469 determined by Moura *et al.* was adopted.[9]

2.2.2 *Sampling plan validation*

We used two validation methods for the sampling plans. The first validation method was based on the operating characteristic (OC) curves and average sample number (ASN).[2,5,17] The second validation method was based on pest sampling in 81 common bean crops.[2,9]

2.2.2.1 Validation based on the operating characteristic (OC) curves and on the average sample number (ASN) for decision making. In the OC and ASN determinations, we used Eqns 11 and 12:[2,5,17]

$$OC = \frac{\frac{(1-\beta)^h - 1}{\alpha}}{\frac{(1-\beta)}{\alpha} - \frac{(\beta)^h}{1-\alpha}} \tag{11}$$

$$ASN = \frac{OC_n\left(h_0 - h_1\right) + h_1}{m - S} \tag{12}$$

where m is the mean number of *E. kraemeri* adults per sample and when $h = m$ is an auxiliary dependent variable. For α, β, h_0, h_1 and S determinations, we used Eqns 8, 9 and 10.

Two vertical line segments were inserted in these graphs, representing the limits of pest control decision making. The first segment represents the lower decision-making limit (m_0), i.e. when the pest population is below this limit, non-control decisions are made. The second segment represents the upper decision-making limit (m_1), i.e. when the pest population is equal to or greater than this limit, control decisions are made.

2.2.2.2 Validation based on conventional sampling plans in common bean crops. In this validation method, we evaluated the densities of *E. kraemeri* in 81 common bean crops. These crops were located in the region of Viçosa, Minas Gerais State, Brazil. In these evaluations, we used the standardized sampling plan developed by Moura *et al.* and the sequential sampling plans developed in the present study.[9] This standardized sampling plan consists of the evaluation of 63 samples per crop. We recorded the average density of the insect obtained by the standardized sampling plan, the number of samples and the decision (control or non-control) of the sampling plans. Then, the percentage of right decisions and the time saved in the sequential sampling plans were calculated. In these comparisons, the standardized sampling plan developed by Moura *et al.* was used.[9]

3 RESULTS

3.1 Economic injury level

The cost of *E. kraemeri* control in common bean crops was US$86.03. A total of 55.52% of this was spent on insecticides, 11.73% on adjuvants and 32.75% on equipment and services (Table 1).

Table 2. *Empoasca kraemeri* economic injury level in common bean according to the crop technological level

Technological level	Productivity (kg ha^{-1})	Production value[a] (US\$ ha^{-1})	Economic injury level		
			Productivity loss[b] (%)	(adults plant^{-1})[c]	(adults sample^{-1})[d]
Low	1200	876.00	8.10	2.87	0.48
Medium	1800	1314.00	5.40	2.34	0.39
High	2400	1752.00	4.05	2.10	0.35

[a] These values were obtained by multiplying the productivity by the average price received by farmers in Brazil in 2015 and 2016 (US\$0.73 kg^{-1}).
[b] Values were obtained from the equation EIL (%) = (100 × control cost)/(0.8 × production value without the pest attack).
[c] Values were obtained from productivity losses (%) in the curve contained in Figure 1A.
[d] Values were obtained by applying the number of adults plant^{-1} in the curve in Figure 1B. This sampling was performed by leaf beating on a plastic tray.

Table 3. *Empoasca kraemeri* (adults sample^{-1}) density (D), sample number in the sequential plan (NSq), decision-making (Ct = decision to control the pest and Nc = decision not to control the pest) and economy (Ec) as a result of the adoption of the sequential plan (Sq) compared with the standardized plan (St = 63 samples per crop) in common bean crops (Cr) with low (EIL = 0.48 adults sample^{-1}), medium (EIL = 0.39 adults sample^{-1}) and high (EIL = 0.35 adults sample^{-1}) technological levels

			Decision-making		Ec			Decision-making		Ec			Decision-making		Ec
Cr	D	NSq	St	Sq	(%)	D	NSq	St	Sq	(%)	D	NSq	St	Sq	(%)
	Low technological level					Medium technological level					High technological level				
1	0.67	43	Ct	Ct	31.75	1.71	12	Ct	Ct	80.95	1.08	16	Ct	Ct	74.60
2	1.06	13	Ct	Ct	79.37	1.22	12	Ct	Ct	80.95	1.24	16	Ct	Ct	74.60
3	0.98	13	Ct	Ct	79.37	1.81	12	Ct	Ct	80.95	0.41	16	Ct	Ct	74.60
4	1.71	13	Ct	Ct	79.37	2.13	12	Ct	Ct	80.95	0.08	34	Nc	Nc	46.03
5	1.17	13	Ct	Ct	79.37	0.05	17	Nc	Nc	73.02	0.11	48	Nc	Nc	23.81
6	0.95	16	Ct	Ct	74.60	0.11	17	Nc	Nc	73.02	0.98	16	Ct	Ct	74.60
7	1.02	13	Ct	Ct	79.37	0.13	38	Nc	Nc	39.68	0.11	18	Nc	Nc	71.43
8	0.94	13	Ct	Ct	79.37	0.06	14	Nc	Nc	77.78	0.08	38	Nc	Nc	39.68
9	1.35	13	Ct	Ct	79.37	0.11	17	Nc	Nc	73.02	0.38	42	Ct	Ct	33.33
10	2.05	13	Ct	Ct	79.37	0.02	14	Nc	Nc	77.78	0.11	22	Nc	Nc	65.08
11	1.73	13	Ct	Ct	79.37	0.83	12	Ct	Ct	80.95	0.13	48	Nc	Nc	23.81
12	1.41	13	Ct	Ct	79.37	0.19	47	Nc	Nc	25.40	0.14	38	Nc	Nc	39.68
13	0.03	13	Nc	Nc	79.37	0.03	14	Nc	Nc	77.78	1.38	16	Ct	Ct	74.60
14	0.06	20	Nc	Nc	68.25	0.37	19	Nc	Ct	69.84	1.57	16	Ct	Ct	74.60
15	0.03	14	Nc	Nc	77.78	4.22	12	Ct	Ct	80.95	2.32	16	Ct	Ct	74.60
16	0.08	15	Nc	Nc	76.19	1.41	12	Ct	Ct	80.95	1.06	16	Ct	Ct	74.60
17	0.02	14	Nc	Nc	77.78	1.57	12	Ct	Ct	80.95	1.98	16	Ct	Ct	74.60
18	0.08	14	Nc	Nc	77.78	1.57	12	Ct	Ct	80.95	1.52	16	Ct	Ct	74.60
19	1.21	13	Ct	Ct	79.37	1.38	12	Ct	Ct	80.95	2.81	16	Ct	Ct	74.60
20	4.22	13	Ct	Ct	79.37	1.57	12	Ct	Ct	80.95	1.27	16	Ct	Ct	74.60
21	0.83	13	Ct	Ct	79.37	1.00	12	Ct	Ct	80.95	1.08	16	Ct	Ct	74.60
22	0.94	13	Ct	Ct	79.37	0.95	12	Ct	Ct	80.95	0.95	16	Ct	Ct	74.60
23	1.17	13	Ct	Ct	79.37	0.83	12	Ct	Ct	80.95	0.68	16	Ct	Ct	74.60
24	0.98	13	Ct	Ct	79.37	0.59	17	Ct	Ct	73.02	0.87	16	Ct	Ct	74.60
25	0.73	13	Ct	Ct	79.37	0.68	12	Ct	Ct	80.95	0.48	28	Ct	Ct	55.56
26	0.68	13	Ct	Ct	79.37	0.62	12	Ct	Ct	80.95	0.349	63	Nc	Nc	0.00
27	0.65	18	Ct	Ct	71.43	0.59	12	Ct	Ct	80.95	0.38	36	Ct	Ct	42.86
Average economy (%)					76.43					75.43					60.55

The curve that described the grain production by plants according to *E. kraemeri* attack intensity was significant ($P < 0.05$) and adjusted to a model with a coefficient of determination (R^2) of 0.95. This curve can be divided into two parts. In the first part, the pest density varied from 0 to 1 adult per plant and grain production showed little variation with pest attack increases. In the second part, the pest density was >1 adult per plant and the grain production of the plants decreased while pest attack increased. The grain yield of the plants decreased by 16% (Figure 1A).

The curve describing the relative densities (insects per sample) obtained by the use of the technique of leaf beating on a plastic tray according to *E. kraemeri* absolute densities (adults per plant) was significant ($P < 0.05$). This curve followed a simple linear model with a coefficient of determination of 0.93 (Figure 1B).

Empoasca kraemeri economic injury levels in terms of plant productivity losses were 8.10, 5.40 and 4.05% for crops with low, medium and high technological levels, respectively (Table 2). The economic injury levels in terms of *E. kraemeri* adults were 2.87,

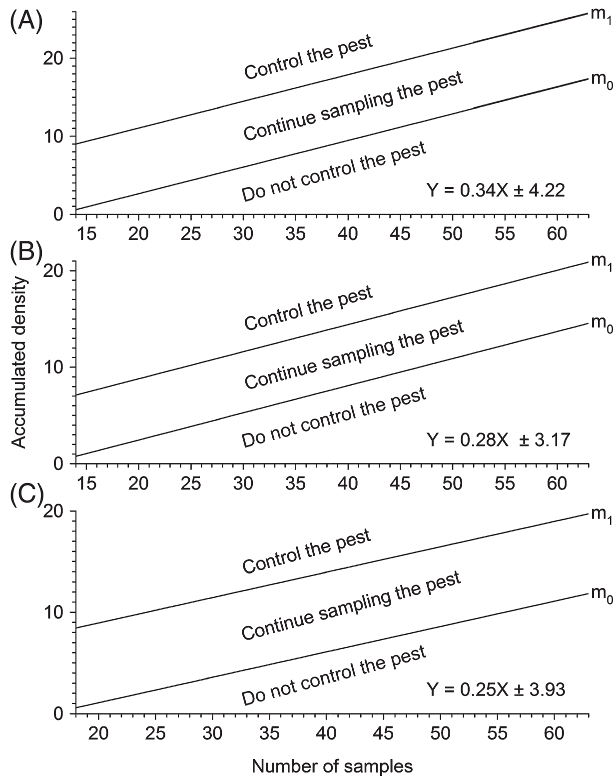

Figure 2. Decision-making limits for adult *Empoasca kraemeri* sequential sampling plans in common bean crops using low (A), medium (B) and high (C) technological levels.

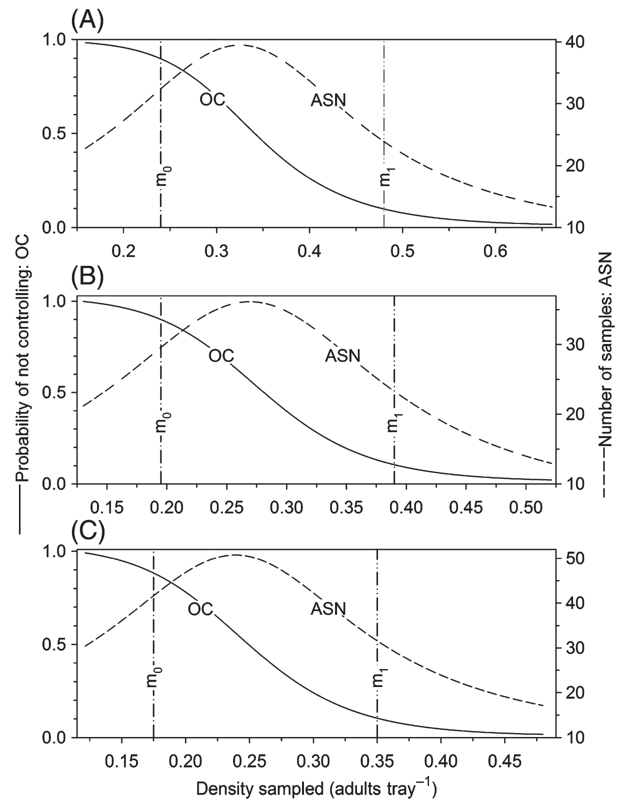

Figure 3. Non-control probability and the mean sample numbers of sequential sampling plan curves for *Empoasca kraemeri* adults in common bean crops using low (A), medium (B) and high (C) technological level curves.

2.34 and 2.10 adults plant^{-1} for crops with low, medium and high technological levels, respectively. Finally, the economic injury levels when using the technique of leaf beating on a plastic tray were 0.48, 0.39 and 0.35 adults sample^{-1} for crops with low, medium and high technological levels, respectively. In the sequential sampling plan determinations shown below, we used, as the unit of economic injury level, the relative density evaluated by the technique of leaf beating on a plastic tray. This was done because this technique is ideal for *E. kraemeri* sampling in common bean crops[12].

3.2 Sequential sampling plans

The lower (m_0) and upper (m_1) boundaries of the sequential sampling plans for low, medium and high technological levels were $m_0 = 0.24$, 0.195 and 0.175 and $m_1 = 0.48$, 0.39 and 0.35, respectively. The slope of the decision-making limits for the sampling plans were $S = 0.34$, 0.28 and 0.25 for low, medium and high technological levels, respectively. The decision-making intercepts (h_0/h_1) were ± 4.22, ± 3.17 and ± 3.93 for low, medium and high technological levels, respectively (Figure 2).

In low technological level crops and medium technological level crops, the minimum (m_0 origin in Figure 2A) and average sample numbers (ASN intersection with m_0 in Figure 3A) to make a decision not to control the pest were 14 and 31 samples, respectively. In these crops, the minimum (m_1 origin in Figure 2A) and average sample numbers (ASN intersection with m_1 in Figure 3A) to make a decision to control the pests were 14 and 22 samples, respectively.

In the case of medium technological level crops, the minimum (m_0 origin in Figure 2B) and average sample numbers (ASN intersection with m_0 in Figure 3B) to make a decision not to control the pest were 14 and 30 samples, respectively. In these crops, the minimum (m_1 origin in Figure 2B) and average sample numbers (ASN intersection with m_1 in Figure 3B) to make a decision to control the pest were 14 and 23 samples, respectively.

In contrast, in high technological level crops, the minimum (m_0 origin in Figure 2C) and average sample numbers (ASN intersection with m_0 in Figure 3C) to make a decision not to control the pest were 18 and 43 samples, respectively. In these crops, the minimum (m_1 origin in Figure 2C) and average numbers (ASN intersection with m_1 in Figure 3C) to make a decision to control the pest were 18 and 32 samples, respectively.

The validation of the sampling plans using the pest monitoring method in 81 common bean crops indicated that in 100% of the low, medium and high technology crops, the sequential and conventional methods led to the same decision. It was observed that, in the low technological level crops, the use of the sequential sampling plan saved 76.41% of the sampling time in relation to the standardized plan. At the medium technological level, the use of the sequential sampling plan saved 75.43% of the sample time in relation to the standardized plan. Finally, at the high technological level, the use of the sequential sampling plan saved 60.55% of the sampling time in relation to the standardized plan (Table 3). Using the standardized sampling plan, it took 17 min to make a decision, while using the sequential sampling plans, these decisions were made in 4, 4 and 7 min in common bean crops using low, medium and high technological levels, respectively.

4 DISCUSSION

Based on the relationship between control costs and the damage that the pest can cause, *E. kraemeri* control decisions in common bean crops are very important for farmers. On the one hand, if the farmer makes control decisions, there is an increase in production costs (as the cost for controlling the pest is 6.48, 4.32 and 3.25% of the production value at low, medium and high technological levels, respectively) and undesirable environmental impacts.[21–23] On the other hand, if the farmer delays making control decisions, losses occur given that *E. kraemeri* attacks can reduce common bean production by up to 16%. Therefore, if the farmer uses the control system defined in this research, the production costs and the losses caused by the pest can be reduced, and the environmental impact caused by improper use of control methods minimized.

Models describing the relationship between plant productivity and pest density may be of three types.[2,6] The first model describes this relationship in pest-tolerant plants and is represented by concave down curves. The second model describes this relationship in plants susceptible to pests and is represented by a line with a negative angular coefficient. The third model describes this relation in plants that are highly susceptible to pests and is represented by concave up curves.

Thus, common bean plants were tolerant to *E. kraemeri* attacks, as the curve that described the relation of the productivity of the plants as a function of the density of the pest was a concave down curve. This can be demonstrated by the fact that an increase of *E. kraemeri* attacks from 0 to 1 adult per plant did not alter grain production. *Empoasca kraemeri* damage to the common bean occurs as a result of the introduction of toxins into the vascular system.[12,13] Thus, this tolerance is possibly attributable to the fact that plants degrade or tolerate low concentrations of these toxins. However, with an increase in pest attacks (density > 1 adult per plant), damage occurred as there was a reduction in grain production by the plants.

The beating tray method was used in the determination of economic damage levels and the development of sampling plans because it enables fast, accurate and representative sampling of *E. kraemeri* attacks on common bean crops.[12]

The economic injury level was lower in high technological level crops because of the higher production value obtained in this situation, as these variables are inversely proportional.[1,2,5,6] This result has implications for integrated pest management programs because the higher the technological level of crops, the lower the pest density required for the farmer to make control decisions.[2,5,6].

In this research, three sequential sampling plans were developed for *E. kraemeri* according to the technological level of the common bean crop. For the three sequential sampling plans, it was possible to make non-control decisions and control decisions according to pest density. Therefore, the sampling plans developed can be used for any *E. kraemeri* attack intensity on common bean crops of different technological levels.

We found that control decisions were made at lower pest densities in the sampling plans for crops with higher technological levels. This was because of the lower economic injury level in this situation.[1,2,5,6,24,25] Therefore, in higher technological level crops, the control decision should be made at lower pest densities as in this situation the economic injury level is lower. In contrast, in plantations with a lower technological level, control decisions must be made at higher densities. Based on the sampling plans formulated in this research, decision-making to control pests should take place at lower attack intensities.

At first, one may think that the pest control decision-making system generated appears overly complex or difficult to implement.[26,27] However, it should be noted that computer software and smartphone applications enable the user to enter information, such as technological level, that facilitates the decision-making process.[28–31]

The advantages of sequential plans over the standardized sampling plans have also been demonstrated in these plan validations. We verified that, in validation processes using the OC curves and in the crop monitoring, sequential sampling plans make decisions similar to the standardized plan generated by Moura *et al.*[9] However, sequential plans make these decisions earlier with a time saving of over 60% in comparison with the standardized plan.

5 CONCLUSIONS

The *E. kraemeri* economic injury levels are 0.48, 0.39 and 0.35 adults per sample when the yield is low (1200 kg ha^{-1}), medium (1800 kg ha^{-1}) and high (2400 kg ha^{-1}), respectively.

The three sequential sampling plans determined for *E. kraemeri* lead to decisions that are similar to those made in the conventional plan. However, sequential sampling plans reduce sampling time, when pest densities are equal to or higher than the economic injury level. Therefore, the economic injury levels and sequential sampling plans generated may be introduced in common bean IPM at different technological levels, as they provide suitable control decisions for *E. kraemeri*.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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