J. Appl. Entomol. **130(3),** 160–166 (2006) doi: 10.1111/j.1439-0418.2005.01032.x

Economic injury level and sequential sampling plan for *Bemisia tabaci* in outdoor tomato

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Ms. received: July 4, 2005; accepted: November 24, 2005

Abstract: This work aimed to determine the economic injury levels and to establish sequential sampling plans for nymphs and adults of the whitefly *Bemisia tabaci* Genn. (Sternorrhyncha: Aleyrodidae) in tomato fields. Densities of nymphs and adults, as well as crop yield were evaluated in 13 commercial tomato fields to determine the economic injury levels. The whitefly nymphs were sampled by direct counting in a leaf from the lower part of the canopy and the adults were sampled by beating an apical leaf against a white plastic tray. The sequential sampling plan was based on data collected in eight commercial tomato fields. The validation of the sequential sampling plan was carried out based on the curves of operational characteristics and average sample numbers. The decisions reached with the conventional and the sequential sampling plans in 21 commercial fields were compared for the intended validation of the sequential plan. The economic injury levels were four nymphs per leaf and one adult per tray. The decisions taken based on the sequential sampling plan were similar to those obtained through the conventional sampling plan. Most of the decisions taken with the sequential sampling plan were obtained through the minimum number of seven samples per field for nymphs and 11 samples per field for adults, with reductions of 84.44% and 54.17% in the number of samples required to reach a decision with the sequential sampling plan compared with the conventional sampling plan.

Key words: *Lycopersicon esculentum*, Brazil, decision-making, Sternorrhyncha, whitefly

1 Introduction

The whitefly, *Bemisia tabaci* Genn. (Sternorrhyncha: Aleyrodidae), is an important agricultural pest throughout the world (Naranjo and Ellsworth, 2001). The nymph and adult stages are critical because of their ability to feed on sap (Lourenção and Nagai, 1994), to inject toxins into the vascular system of plants, to induce irregular ripening of fruits (Powell et al., 1998) and to transmit viral diseases to tomato plants (Czosnek et al., 1988). The damage potential of whitefly is very high and farmers usually spray high amount of insecticides for controlling this pest in tropical tomato fields. The low susceptibility of the whitefly to many insecticides and the reduction of its natural enemy populations, because of applications of non-selective compounds, are factors that have contributed to the increase in the whitefly population in crops (Lourenção and Nagai, 1994; Byrne and Devonshire, 1997).

The extensive use of insecticides has resulted in heavy economic and environmental losses (Imenes et al., 1992; Stansly et al., 1998). Therefore, the development and implementation of an integrated whitefly management programme are necessary for a more sustainable approach to control this pest species reducing insecticide use and minimizing the existent environmental problems besides maintaining or enhancing economic crop viability. It is necessary to estimate the damage caused by this insect on the tomato field and to determine the population density capable of causing economic loss for the implementation of an integrated management programme. Economic damage is defined as the economic value of losses necessary to equal the economic costs of management (Stone and Pedigo, 1972). The ratio between the management cost and crop value is the expression of yield loss necessary to justify the management, which is called gain threshold. The insect numbers necessary to produce equivalent losses to the gain threshold is the economic injury level (Higley and Pedigo, 1996). Although great yield losses are reported as resulting from whitefly attack, there is a lack of studies quantifying these losses. Such studies are necessary for the determination of decision-making parameters to control *B. tabaci*.

The insect population should be determined by sampling plans and compared with the economic injury level for decision-making regarding insect control. Therefore, it is necessary to determine a fast and precise sampling plan to estimate the whitefly populations for the implementation of a sound pest management programme (Fowler and Lynch, 1987). There are two types of sampling plans for the relative estimation of insect populations – the conventional and the sequential sampling plans. The conventional sampling plan represents the initial generation of a decision-making system in integrated pest management programmes because of its easy adoption. It allows the determination of essential parameters that are important for the establishment of a sequential sampling plan, such as economic injury level, sampling unit and sampling technique (Pedigo et al., 1982). Gusmão et al. (2005) determined conventional sampling plans for nymphs and adults of whitefly in outdoor tomato field, which were characterized by the direct counting of the nymphs on a basal leaf of the plant canopy and by counting the adults after beating the apical leaf of the tomato canopy in a plastic tray. The required sample numbers were 45 and 24 samples per field for sampling nymphs and adults respectively.

The sequential plan was developed as a rapid quality control evaluation tool during World War II (Wald, 1945) and it was subsequently adapted for use in integrated pest management programmes because of the lesser effort required than programmes of fixed number of samples, as in the conventional sampling plans (Waters, 1955; Ruesink and Kogan, 1982). There are several methodologies for the determination of the sequential sampling plan. Wald (1945, 1947) developed the sequential probability ratio test based on the probability ratio of Newman–Pearson to obtain the decision boundaries. Green (1970) presented a method using derived parameters of Taylor's power law (Taylor, 1961) to determine a critical stop line. Iwao (1975) described a method using Lloyd's index of mean crowding (Lloyd, 1967) and linear regression techniques recognized as Iwao's confidence interval method.

Considering the importance of whitefly control guided by population estimations, this work aimed to determine the economic injury levels and to establish sequential sampling plans for nymphs and adults of *B. tabaci* in outdoor tomato crop.

2 Materials and Methods

2.1 Determination of the economic injury level

The populations of nymphs and adults of whitefly were evaluated from February to July 1999, in 13 commercial tomato fields, variety Santa Clara Asgrow, with a 1.0×0.50 m spacing and in the reproductive phase (about 70 days after seedling transplantation) (table 1). The crop fields were located at Coimbra and Guidoval counties, State of Minas Gerais, Brazil. The fruits were manually picked twice a week and the yields were recorded as tons per hectare. The whitefly nymphs were sampled by direct counting in a leaf from the lower part of the canopy and the adults were sampled by beating an apical leaf against a white plastic tray (30 cm width $\times$ 45 cm length $\times$ 5 cm depth) (Gusmão et al., 2005).

The curves of yield loss were obtained by regression analysis with nymphs per leaf, adults per tray and yield as independent variables. The data were adjusted to the exponential, linear, quadratic, cubic and inverse regression models. The choice of the best regression model was based on the significance of the regression ($P < 0.05$), determination coefficient (R^2) and significance of the equation coefficients ($P < 0.05$).

The estimation of the economic damage was based on the value of the losses caused by an insect population which equals its control cost (CC) and the expenses incurred by three insecticide applications (number usually used by the producers) for the control of whitefly during the tomato cultivation. The recommended insecticide was imidacloprid [70 WG] [200 active ingredient (a.i.)/ha applied with a volume of 500 L/ha], the price of which during the research period was US\$0.28 per gram. The labour expense was US\$3.20 per day, based on the wage of the spraying worker with an operational capacity of 120 L of solution per day in a workday of 8 h. The CC in US\$ per hectare was transformed in tomato tons per hectare (t/ha) using the averaged market value of US\$181.78 per ton, which was the tomato commercialization value during the period of data collection at the State Center of Agricultural Provision (CEASA-MG). The potential yield (PY; ton/ha) was estimated from the yield loss equations, considering the null density of insects. The real yield (RY) of tomato in ton/ha was estimated by subtracting the cost of insect control from the value of the potential yield with insect damage. The economic injury levels were the insect densities (x-value) in the regression equations which

Table 1. *Area, number of plants, yield and whitefly densities in the sampled fields*

Field	County	Area (ha)	Number of plants	Yield (ton/ha)	Whitefly densities (mean ± SE)	
					Adults per tray	Nymphs per leaf
1	Coimbra	0.16	3200	38.83	19.40 ± 3.08	202.28 ± 27.98
2	Coimbra	0.15	3000	38.83	76.69 ± 8.62	213.72 ± 34.78
3	Coimbra	0.11	2300	38.83	63.72 ± 11.11	219.64 ± 34.69
4	Coimbra	0.18	3600	84.03	2.53 ± 0.31	58.09 ± 6.58
5	Coimbra	0.18	3600	84.03	5.89 ± 1.15	51.83 ± 6.02
6	Coimbra	0.05	1000	34.71	98.06 ± 10.75	740.23 ± 99.09
7	Coimbra	0.04	800	34.71	108.88 ± 8.64	736.33 ± 97.02
8	Coimbra	0.60	12 000	101.20	0.93 ± 0.14	1.54 ± 0.25
9	Coimbra	0.20	4000	125.09	0.69 ± 0.14	6.65 ± 1.56
12	Coimbra	0.18	3500	114.16	11.74 ± 1.46	52.80 ± 8.79
10	Guidoval	0.14	2800	56.26	8.60 ± 0.99	10.20 ± 1.45
11	Guidoval	0.40	8000	56.57	25.20 ± 2.87	40.46 ± 4.54
13	Guidoval	0.35	7000	77.22	20.65 ± 1.50	37.78 ± 3.92

corresponded to the yield values (y-values) equal to real yield.

2.2 Determination of the sequential sampling plan

The sequential sampling plan had the tomato leaf as the sample unit and the quantified variables were the number of nymphs per leaf and number of adults per tray. The data were adjusted to the frequency distribution models of Poisson and negative binomial, which described the distributions of the variables, allowing the construction of the plan. The whitefly data collected by Gusmão et al. (2005) for the conventional sampling plan were used to generate the sequential sampling plan. The data were collected from eight commercial outdoor tomato fields, variety Santa Clara Asgrow, with 1.0×0.5 m spacing during the reproductive phase (about 70 days after seedling transplantation). The data were adjusted to the negative binomial model with the common K-values of 0.737 for nymphs and 1.098 for adults. The sequential sampling plans were determined by the Wald's sequential probability ratio test (Wald, 1945, 1947; Fowler and Lynch, 1987; Bates et al., 1991; Nault and Kennedy, 1996; Boeve and Weiss, 1997; Naranjo et al., 1997), where the intercept values of lower (h_0) and upper (h_1) boundaries and the inclination values of these limits of decision (S) were obtained through the equations described by Pedigo and Zeiss (1996).

Two critical densities (m_0 – critical density at the lower boundary, equal to one-third of the economic injury level; m_1 – critical density of the upper boundary, equal to two-thirds of the economic injury level) were estimated from the economic injury levels (Hammond and Pedigo, 1976). Economic damage will not take place when the insect density stays below the lower boundary (null hypothesis) and it will take place when the insect density surpasses the upper boundary (alternative hypothesis). The maximum probability levels of making mistakes in estimating insect densities [i.e. probability of predicting an insect density as non-harmful when it is so (a type I error), and the probability of predicting an insect density as harmful when it is not so (a type II error)] were $\alpha = \beta = 10\%$.

The sample size in the sequential plan depended on the values of the observations made. The decision to accept or to reject the null hypothesis leading to the decision to stop sampling or to control the insect by applying insecticides was made after each observation, and the observations were carried on until having sufficient data to make one of the decisions (Ruesink and Kogan, 1982; Fowler and Lynch, 1987).

2.3 Validation of the sequential sampling plan

Curves of operational characteristics and average sample numbers were determined for validation of the sequential sampling plan according to the methodology described by Fowler and Lynch (1987). The curve of operational characteristics shows the probability of deciding not to control the insects as a function of the insect density. The curve of the average sample number indicates the required sample number for decision-making as a function of the insect density.

Besides these analyses, the densities of whitefly nymphs and adults present in 21 commercial tomato fields were determined using the conventional sampling plans of Gusmão et al. (2005) and also using the sequential sampling plans reported here. The decision-making for managing whitefly nymphs and adults from both sampling plans were compared and the economy obtained by the reduction of the requested sample number was determined.

3 Results

The increase of whitefly nymph and adult densities led to a reduction in yield (table 2 and fig. 1). The exponential model was the best for adjusting the data as it is sufficient to explain a large part of the variability and fits best to the biological background

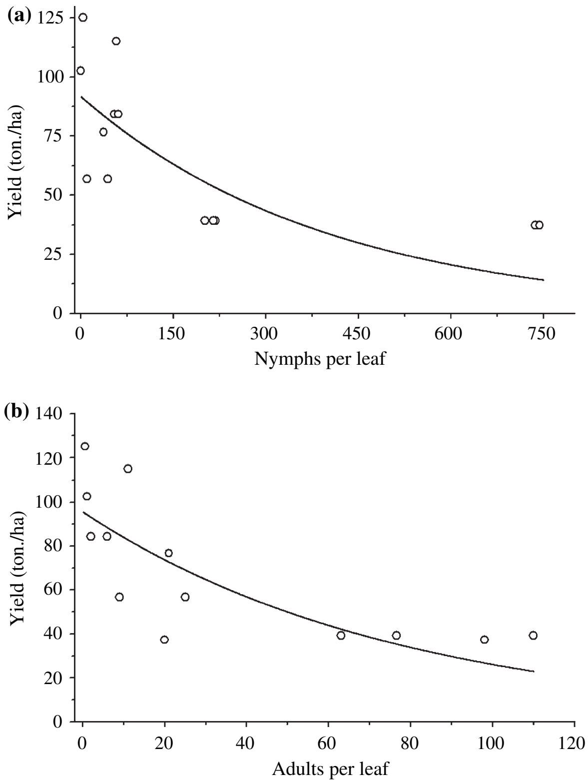

Fig. 1. Yield as a function of the density of nymphs (a) and adults (b) of B. tabaci. *Symbols represent mean of 65 replicates*

Table 2. The best curve fitting models of yield as a function of whitefly densities after testing five regression models (linear, quadratic, cubic, exponential and inverse)

Model	Coefficient	Value	Standard error	t	P	P-value of regression model	R^2
Nymphs							
Exponential ($y = a * e^{-bx}$)	a	91.74	9.95	9.22	< 0.0001	0.0018	0.60
	b	0.0025	0.0011	2.39	0.036		
Adults							
Exponential ($y = a * e^{-bx}$)	a	95.52	9.0970	10.50	< 0.0001	0.0008	0.65
	b	0.013	0.0042	3.17	0.0088		

parameters ($R^2 = 0.60$, $P = 0.002$ for nymphs and $R^2 = 0.65$, $P = 0.001$ for adults) (table 2 and fig. 1).

The CC for whitefly nymphs and adults using three sprayings of imidacloprid were US$207.27/ha or about 0.95 tons of tomato per hectare. The yields were 91.74 and 95.51 ton/ha in the absence of whitefly nymphs and adults, respectively, based on the regression equations of yield losses as a function of whitefly density. However, the real yields were 90.79 ton/ha due to the damage caused by nymphs and 94.56 ton/ha due to the damage caused by adults considering the economic damage caused by these insects, which corresponds to its CCs. Thus, the whitefly densities capable of causing damage equivalent to its CCs were four nymphs per leaf and one adult per tray. These densities are the values of economic injury levels for nymphs and adults of whitefly in outdoor tomato fields (fig. 1 and table 3).

The critical densities in the lower (m_o) and upper (m_1) boundaries of the sequential sampling plan for nymphs were $m_o = 1.33$ nymphs per leaf and $m_1 = 2.67$ nymphs per leaf. The slope of the decision boundary of the sampling plan for nymphs was $S = 1.87$ and the intercepts were $h_o = -11.14$ for the lower boundary and $h_1 = 11.14$ for the upper boundary. The minimum number of samples for the decisions of not controlling, keep sampling or controlling based on nymph density was seven samples (fig. 2).

The critical densities in the lower (m_o) and upper (m_1) boundaries of the sequential sampling plan for adults were $m_o = 0.33$ adults per tray and $m_1 = 0.67$ adults per tray. The slope of the decision boundary of the sampling plan for adults was $S = 0.47$ and the intercepts were $h_o = -4.44$ for the lower boundary and $h_1 = 4.44$ for the upper boundary. The minimum number of samples for the decisions of not controlling, keep sampling or controlling based on adult density was 11 samples (fig. 2).

Three decision zones are defined by the critical boundaries for decision-making shown in the fig. 2. The first represents the insect density below which the sampling should be interrupted and the decision of not controlling the insects is made (it accepts the null hypothesis). The second is determined by the insect density above which insect control is necessary (it accepts the alternative hypothesis), that is, densities above this limit cause economic damages. Finally, the third decision zone is represented by the intermediary insect densities in which sampling should continue until reaching one of the decision boundaries. There is a 90% probability ($\alpha = \beta = 10\%$), based on fig. 2, that the accumulated density of nymphs and adults will be placed below or above the economic damage, and therefore one of the decisions (to stop the sampling and not controlling the insects, to continue the sampling or to make the decision of controlling the insects) should be taken.

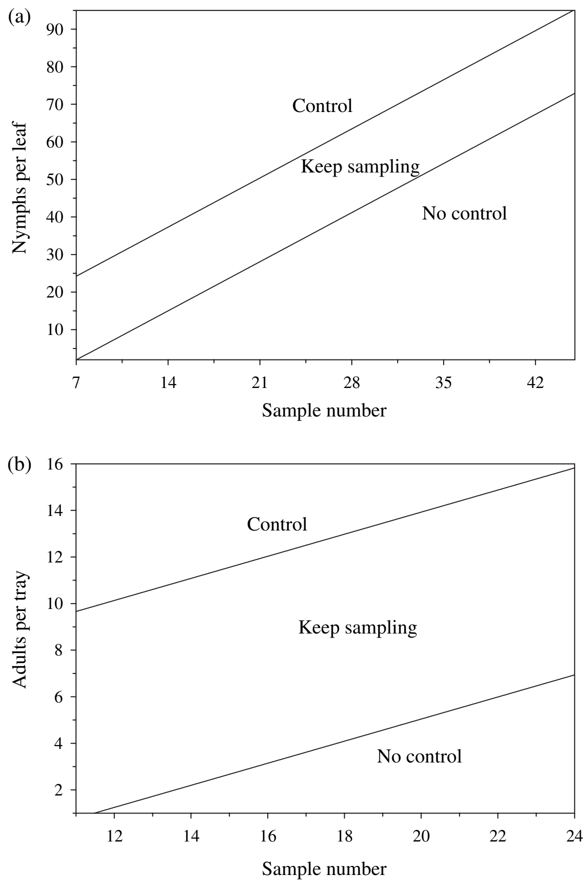

Fig. 2. *Decision boundaries of the sequential sampling plan for whitefly nymphs (a) and adults (b) in outdoor tomato*

A group of 12 samples per field was necessary for the decision of stopping the sampling and not controlling the whitefly when the densities of nymphs were close to the critical density of the lower boundary (1.33 nymphs per leaf). In contrast, for densities of nymphs close to the critical density of the upper boundary (2.67 nymphs per leaf), about 18 samples per field were necessary for the decision of stopping the sampling and controlling the whitefly. For densities close to the economic injury level (four nymphs per leaf), the necessary number of samples to reach a decision was lower than 10 samples per field (fig. 3a).

The probability of deciding not to control the whitefly when the density of nymphs was close to the critical density of the lower boundary (1.33 nymphs per leaf) was 100%. In contrast, for densities of nymphs above the critical density of the upper boundary (>2.67 nymphs per leaf), the probability of not controlling was lower than 50%. The probab-

Table 3. *Values of yield, control cost, whitefly damage and economic injury levels*

Characteristic	Value
Yield (US$ per ton)	218.18
Number of insecticide sprayings to control whitefly	3
Control cost for whitefly (ton/ha)	0.95
Potential yield as function of whitefly nymphs (ton/ha)	91.74
Potential yield as function of whitefly adults (ton/ha)	95.51
Real yield as function of whitefly nymphs (ton/ha)	90.79
Real yield as function of whitefly nymphs (ton/ha)	94.56
Economic injury level for whitefly nymphs (nymphs per leaf)	4
Economic injury level for whitefly adults (adults per tray)	1

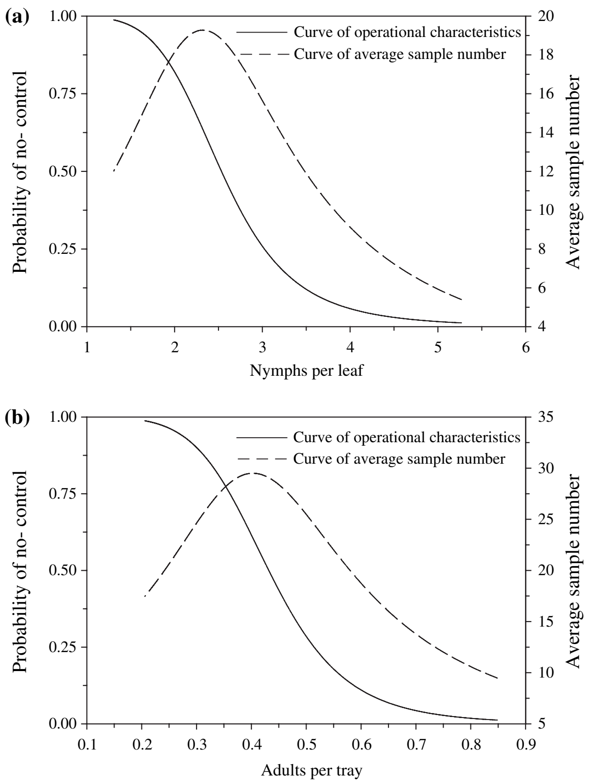

Fig. 3. *Curves of operational characteristics and average sample number for the sampling of whitefly nymphs (a) and adults (b) in outdoor tomato*

ility of deciding not to control the whitefly when the densities of nymphs were similar to critical density of the economic injury level (four nymphs per leaf) was lower than 10% (fig. 3a).

A group of 26 samples per field was necessary to decide stopping the sampling and not controlling the insects when the adult density was close to the critical density of the lower boundary (0.33 adults per tray). For adult densities close to the critical density of the upper boundary (0.67 adults per tray), about 15 samples per field were necessary for deciding to stop the sampling and controlling the whitefly. For densities close to the economic injury level (one adult per tray), the necessary number of samples to reach a decision was smaller than 10 samples per field (fig. 3b).

The probability of deciding not to control the whitefly when the densities of adults were close to the critical density of the lower boundary (0.33 adults per tray) was larger than 90%. In contrast, for adult densities above the critical density of the upper boundary (> 0.67 adults per tray), the probability of not controlling was smaller than 10%. A null probability was verified for the decision of not controlling the whitefly when the densities of adults were similar to the critical density of the economic injury level (one adult per tray) (fig. 3b).

The decisions obtained with the conventional sampling plans were similar to those obtained with the sequential sampling plans for both nymphs and adults of whitefly (table 4). The only decisions which did not match in both sampling plans were those of not controlling the insects obtained with conventional sampling plan of adults at the fields 10, 18 and 19 (table 4). Decisions were usually reached with the minimum number of samples (seven samples per field in the sampling of nymphs and 11 samples per field in the sampling of adults) for most of the sampled fields using the sequential sampling plans. Therefore if the farmers adopt the sampling plan, they will make control decisions with a number of samples about 84.44% and 54.17% smaller than in the conventional plan for sampling of nymphs and adults, respectively (table 4). In other words, the farmers who adopt the sequential plan will reduce their cost and time of sampling.

4 Discussion

The lower economic injury level for adults when compared with nymphs is probably because of the greater adult capacity of reducing the yield. This fact is reinforced by the significant difference between the slopes of the yield loss curves, obtained through the negative exponential model for adults and nymphs. The slope of the regression curve for adults (−0.0132 ± 0.0042) is about five times larger than the slope of the regression curve for nymphs (−0.0025 ± 0.0011) (table 2). Therefore, the damage potential of adults is about five times larger than that of nymphs because of an enhanced probability of virus transmission by dispersing adults (Jovel et al., 2000a,b).

Although whitefly nymph or adult populations can reach densities that justify a decision in the first samples, a minimum of seven and 11 samples is necessary per field for a sound decision regarding the sampling of nymphs and adults respectively. However, if the accumulated insect density during the sampling remains between the lower and upper boundaries until reaching a maximum number of 45 and 24 samples per field for nymphs and adults, respectively (number of samples determined for the conventional plan, in agreement with Gusmão et al., 2005), the sampling should be stopped and the growers should return to the field 4 days later to repeat sampling. This time interval for re-sampling is based on the developmental time necessary for the whitefly to reach the third instar and adult stages (Villas Boas et al., 2002).

The curves of operational characteristics and average sample number for nymphs and adults provide further insight into its value. When the populations of nymphs and adults are either low or high, decisions can be made more rapidly and with a high degree of probability of making a correct decision. A reduction of 73.33% in the required number of samples would be obtained with the sequential plan (12 samples per field) instead of the conventional plan (45 samples per field) based on the critical density of nymphs at the lower boundary (1.33 nymphs per leaf). For critical densities close to the upper boundaries (2.67 nymphs per leaf and 0.67 adults per tray), the reduction reaches 60% in the number of samples for nymphs and 37.5% in the

Table 4. *Validation of the sequential sampling plans for whitefly nymphs and adults as a function of the decision reached using conventional sampling plans in 21 tomato fields.*

	Mean no. of nymphs per leaf		Number of samples		Decision-making		
Fields	Conventional plan	Sequential plan	Conventional plan	Sequential plan	Conventional plan	Sequential plan	Economy (%)*
Nymphs							
1	104.00	126.29	45	7	Control	Control	84.44
2	111.00	147.43	45	7	Control	Control	84.44
3	29.00	81.14	45	7	Control	Control	84.44
4	25.00	44.00	45	7	Control	Control	84.44
5	24.00	32.86	45	7	Control	Control	84.44
6	0.71	0.00	45	7	No-control	No-control	84.44
7	0.78	0.67	45	9	No-control	No-control	80.00
8	440.00	180.71	45	7	Control	Control	84.44
9	477.00	642.43	45	7	Control	Control	84.44
10	1.56	1.25	45	20	No-control	No-control	55.56
11	1.89	1.48	45	31	No-control	No-control	31.11
12	6.47	15.29	45	7	Control	Control	84.44
13	6.07	3.33	45	9	Control	Control	80.00
14	0.04	0.00	45	7	No-control	No-control	84.44
15	0.02	0.14	45	7	No-control	No-control	84.44
16	8.53	3.43	45	7	Control	Control	84.44
17	11.38	11.57	45	7	Control	Control	84.44
18	38.44	35.29	45	7	Control	Control	84.44
19	39.40	28.71	45	7	Control	Control	84.44
20	54.60	46.71	45	7	Control	Control	84.44
21	47.44	46.00	45	7	Control	Control	84.44
Fields	Mean no. of adults per tray		Number of samples		Decision-making		Economy (%)
Adults							
1	34.00	36.09	24	11	Control	Control	54.17
2	40.00	37.91	24	11	Control	Control	54.17
3	33.00	31.27	24	11	Control	Control	54.17
4	0.88	1.09	24	11	Control	Control	54.17
5	1.54	1.27	24	11	Control	Control	54.17
6	1.29	1.45	24	11	Control	Control	54.17
7	1.42	1.00	24	15	Control	Control	37.50
8	0.96	1.18	24	11	Control	Control	54.17
9	0.21	0.24	24	17	No-control	No-control	29.17
10	0.42	0.42	24	24	No-control	re-sampling	0.00
11	3.46	0.75	24	16	Control	Control	33.33
12	32.00	42.27	24	11	Control	Control	54.17
13	29.00	38.64	24	11	Control	Control	54.17
14	23.00	29.64	24	11	Control	Control	54.17
15	0.46	0.15	24	13	No-control	No-control	45.83
16	0.83	0.74	24	19	Control	Control	20.83
17	1.38	0.45	24	22	Control	Control	8.33
18	0.42	0.42	24	24	No-control	re-sampling	0.00
19	0.54	0.54	24	24	No-control	re-sampling	0.00
20	0.92	0.94	24	18	Control	Control	25.00
21	0.21	0.24	24	17	No-control	No-control	29.17

number of samples for adults in favor of the sequential sampling plan compared with the conventional sampling plan. When the densities of nymphs and adults were similar to critical density of the economic injury level (four nymphs per leaf and one adult per tray) the reduction in the required number of samples reaches 77.77% for nymphs and 58.33% for adults in favour of the sequential sampling plan compared with the conventional sampling plan.

The similar decisions obtained here with the sequential sampling plans and the conventional sampling plans determined by Gusmão et al. (2005) confirm the precision of the sequential sampling estimations. The no-control decisions, with the conventional sampling plan, and re-sampling decisions, with the sequential sampling for adults in the fields 10, 18 and 19 were due to the densities of adults in those fields being close to the critical densities of the decision boundaries (m_o and m_1). As a consequence, these fields required larger number of samples to reach a decision with the sequential sampling plan. However, for the other fields where the decision was similar for both plans, the sequential sampling showed a reduction of about 84.44% in the time spent in the sampling of nymphs and 54.17% in the time spent in the sampling of adults compared with the fixed number of samples established for the conventional sampling plan.

Acknowledgements

We would like to express our gratitude to the tomato growers who allowed us to use their fields for this study, which was financially supported by the CAPES Foundation (Brazilian Ministry of Education), the National Council of Scientific and Technological Development (CNPq, Brazilian Ministry of Science and Technology) and the Minas Gerais State Agency for Research Aid (FAPEMIG).

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