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The Use of Wald's Sequential Probability Ratio Test (SPRT) in Cocoa Pod Borer Management

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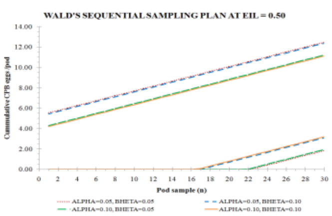
Graphical abstract



Abstract

Sequential sampling plan (SSP) has been widely used in many engineering and quality control study. The advantage of using the SSP is the sample size is not fixed in advance, but is determined in part by the results of the sampling process. The application of the SSP is not limited to the industry, it also being used in pest management. This is because the SSP are generally more cost effective than plans based on a fixed sample size. *Wald's Sequential* Probability Ratio Test (SPRT) is one of the most common *sequential sampling plans* in insect pest management. It has been used to determine pest status at one time which could be used, through time, to monitor the status of the population and to take action when the pest density exceeded the Economic Threshold Level (ETL). Cocoa pod borer or CPB (*Conopomorpha cramerella* (Snell)) is a pest of concern to the cocoa growers in South-East Asia that has become one of the major factors that dampened the interest expressed in cocoa cultivation because of the heavy losses of cocoa pods due to the pest if effective control measure is not employed. The chemical control appeared to be one of the effective control measure used by the growers to control the CPB. Current practice used by the growers in applying the chemical is biweekly spraying which could see the increasing cost of chemical and labor used. The study was conducted to develop the Wald's SPRT to monitor the CPB infestation level relative to the ETL based on counting the CPB eggs found on the pods aged 1 month before ripen or pod length 131 mm to 150 mm. The performance of the Wald's SPRT was validated using independent data sets collected from Cocoa Research and Development Center (CRDC) Madai.

Keywords: Cocoa pod borer; cocoa; sequential sampling plan; Wald's SPRT

Abstrak

Pelan pensampelan jujukan (PPJ) telah digunakan dengan meluas dalam kebanyakan kajian kejuruteraan dan kawalan kualiti. Kelebihan menggunakan PPJ ialah saiz sampel tidak ditetapkan terlebih dahulu, tetapi ditentukan secara pecahan berdasarkan kepada keputusan proses pensampelan. Aplikasi PPJ tidak terhad kepada industri, ia juga digunakan dalam pengurusan perosak. Ini kerana PPJ adalah lebih kos efektif berbanding saiz sampel yang tetap. *Wald's Sequential Probability Ratio Test* (SPRT) adalah salah satu pelan pensampelan jujukan yang biasa digunakan dalam pengurusan perosak. Ia digunakan untuk menentukan status perosak pada satu masa dengan memantau status populasi dan membuat kawalan apabila populasi perosak melebihi Tahap Ambang Ekonomi (TAE). Ulat pengorek buah koko atau UPBK (*Conopomorpha cramerella* (Snell)) adalah perosak utama kepada penanam koko di Asia Tenggara. Serangan UPBK merupakan salah satu faktor utama menyebabkan minat penanaman koko berkurangan kerana kerugian yang tinggi terpaksa ditanggung penanam koko sekiraanya kawalan yang efektif tidak dilaksana. Kawalan kimia merupakan salah satu kawalan yang efektif yang digunakan oleh penanam koko untuk mengawal UPBK. Buat masa sekarang, para penanam menpraktiskan semburan racun serangga secara dua minggu yang menyebabkan penambahan kos racun kimia dan penggunaan tenaga buruh yang tinggi. Kajian ini dilaksanakan untuk menghasilkan *Wald's SPRT* untuk memantau tahap serangan UPBK relatif kepada TAE berdasarkan kiraan telur UPBK yang dijumpai pada buah koko berumur 1 bulan sebelum masak atau panjang buah 131 mm hingga 150 mm. Pengesahan prestasi *Wald's SPRT* dibuat menggunakan data yang dikutip dari Pusat Penyelidikan dan Pembangunan Koko (PPPK) Madai.

Keywords: Ulat pengorek buah koko; koko; pelan pensampelan jujukan; *Wald's SPRT*

1.0 INTRODUCTION

The sequential sampling plan (SSP) has been widely used in many engineering and quality control study. Besides that, SSP is also applied in pest management. This is because the sequential sampling plans can reduce sampling time by more than 50% and cost effective as compared to fixed sample size.[1] There are two sequential sampling plans widely used in pest management, namely the sequential decision plan and sequential counting plan. The sequential decision plan is intended for use in practical control programs where treatment decisions are being made, while the sequential counting plan is used as a research tool for estimating population levels for research purposes. The *Wald's Sequential* Probability Ratio Test (SPRT) is one of the sequential decision plans. In pest management, the Wald's SPRT is used to check whether the estimated pest density is lower or higher than a preset critical level which is normally the threshold level for taking control measures against the pest. The sampling involved in the Wald's SPRT will continue until the sample indicate that one alternative (e.g. not to apply insecticide) is more likely true than the other at a specified acceptable level of probability. However, development of Wald's SPRT requires knowledge on the distribution of the insects on the sample unit. There are few distributions available and the Wald's SPRT equation for insect pest management commonly used the distribution of Normal, Poisson, Binomial and Negative Binomial.[1,2] The most widely used distribution in Wald's SPRT is the negative binomial. The Wald's SPRT has been used in forest and agricultural cropping systems.[3,4]

Cocoa pod borer or CPB (*Conopomorpha cramerella* (Snell)) is a pest of concern to the cocoa growers in South-East Asia. It has become one of the major factors that dampened the interest in cocoa cultivation because of the heavy losses of cocoa pods due to the pest if effective control measure is not employed. Chemical control is one of the effective control measure used by the growers to control the CPB. Current practice used by the growers in spraying the pesticide biweekly which add to cost of production. However, the concept of the pest control should be based on economic as well as ecological considerations where the insecticide is applied to prevent damage that exceed the cost of control. The effectiveness of pest control on CPB can only be conducted when the level of CPB damage on the beans is known. The level of CPB damage on the beans is a function of the pest population density.[5] The best indicator to represent the pest population density is the eggs because it allows more timely treatment applications.[6] By using the sequential sampling plan to monitor the CPB eggs density to initiate the insecticide spraying, it can save the cost and time in controlling the CPB damages since less samples needed.

Therefore, the study was conducted to develop the Wald's SPRT to monitor the CPB infestation level relative to the Economic Threshold Level (ETL) which will equal to the Economic Injury Level (EIL) based on counting the CPB eggs found on the pods aged 1 month before ripening (MBR) or pod length between 131mm to 150mm as it has a strong relationship between wet bean loss and CPB eggs.[7]

2.0 MATERIALS AND METHODS

The study was conducted at Field 55, Cocoa Research and Development Center (CRDC) Madai, Sabah in the year 2011. The plot size is about 1.0 ha which is planted with cocoa monocrop with clonal materials with spacing of 3 m × 3 m. Sixty (60) trees were randomly selected. CPB eggs were examined on all cocoa pods aged 1 MBR or pod lengths between 131 mm to 150 mm. The data collected during the study were number of CPB eggs per pod, pod length and diameters from January 2011 till June 2011. A total of 15 samples were collected from Field 55, CRDC Madai and 9 samples were used in developing the Wald's SPRT and 6 samples to validate the sequential sampling plan.

The CPB eggs data were arranged in frequency distribution and the spatial distribution pattern of the CPB eggs population was fitted to Negative Binomial Distribution (NBD) and tested with goodness of fit test. The NBD is one of the most widely used distributions to characterize aggregated populations.[8] The probability of a sample unit containing x insects is given as follows:[9]

$$P(x) = \frac{(k+x-1)!}{x!(k-1)!}\left(\frac{\mu}{k}\right)^{x}\left(1+\frac{\mu}{k}\right)^{-(x+k)} \quad x = 0,1,2,.. \qquad (1)$$

where x is the number of insects, μ is the mean and k is an index of aggregation.

The negative binomial k was used to measure the aggregation of the CPB eggs population for each 9 samples and the formula used to measure the parameter k was calculated from the sample mean ($\bar{x}$) and sample variance (s^2) as follows:[9]

$$\hat{k} = \frac{\bar{x}^2}{s^2 - \bar{x}} \qquad (2)$$

As k becomes smaller, the degree of clumping increases; and as the value of k increases, the NBD approaches the random Poisson.[10] Waters (1955) suggested that as $k > 0$ (aggregated), $k = 0$ (random) and $k < 0$ (regular). Since the k is not always consistent and changes with the mean, the common k which is also known as the value of the dispersion parameter common (K_c) is necessary in developing the Wald's SPRT whose spatial distribution can be described by the NBD model.[1] In order to estimate the K_c, k estimates of 9 samples were then evaluated using regression procedures to determine if a single, common k (K_c) existed.[11] The development of Wald's SPRT based on the NBD which involved determination on the intercept values of lower (h_0) and upper (h_1) boundaries and the inclination values of these limits of decision (S) can be derived using formula as follows;[12]

$$D_L = Sn + h_0 \text{ (Lower)} \qquad (3)$$
$$D_U = Sn + h_1 \text{ (Upper)} \qquad (4)$$

where D_i is the cumulative CPB eggs count till ith sample while the slope (S) and intercepts (h_0 and h_1) are defined as

$$s = k\frac{\log\left[\frac{1+\frac{m_1}{k}}{1+\frac{m_0}{k}}\right]}{\log\left[\frac{\left(\frac{m_1}{k}\right)\left(1+\frac{m_0}{k}\right)}{\left(\frac{m_0}{k}\right)\left(1+\frac{m_1}{k}\right)}\right]} \qquad (5)$$

$$h_0 = \frac{\log\left(\frac{\beta}{1-\alpha}\right)}{\log\left[\frac{\left(\frac{m_1}{k}\right)\left(1+\frac{m_0}{k}\right)}{\left(\frac{m_0}{k}\right)\left(1+\frac{m_1}{k}\right)}\right]} \text{ and } h_1 = \frac{\log\left(\frac{1-\beta}{\alpha}\right)}{\log\left[\frac{\left(\frac{m_1}{k}\right)\left(1+\frac{m_0}{k}\right)}{\left(\frac{m_0}{k}\right)\left(1+\frac{m_1}{k}\right)}\right]} \qquad (6)$$

D_L and D_U are the lower and upper bound of the sequential sampling plan, k is the index of aggregation, n is the number of pod samples taken, m_0 is the CPB eggs density below which intervention is not needed (null hypothesis), m_1 is the CPB eggs density above which intervention is needed (alternative hypothesis), α is the type I error (risk of concluding that the infestation is high when it is in fact low), and β is the type II error (risk of concluding that the infestation is low when it is high).

The m_0 and m_1 were set to be equal to one-third and two-thirds of the EIL, respectively. The value of EIL used was 0.45

eggs/pod at 1MBR.[1] This value was estimated based on the operational cost of RM1,367.50/ha/yr which covered the labour cost and 24 rounds insecticide application per ha per year in field 55, CRDC Madai and cocoa wet bean yield of RM2,100.00/ha/yr and wet bean yield loss rate of 1.60g/egg/pod.

Curves of operational characteristics (OC) and average sample numbers (ASN) were determined for validation of the Wald's SPRT using the methods described by Fowler and Lynch (1987).[2] The curve of OC shows the probability of deciding not to control the insects as a function of the insect density. The curve of the ASN indicates the required sample number for decision-making as a function of the insect density. The Wald's SPRT were designed for two EILs, EIL = 0.50 (m_0 = 0.17 and m_0 = 0.33) and EIL = 1.00 (m_0 = 0.33 and m_0 = 0.67), at each of the four combinations of α (0.05 or 0.10) and β (0.05 or 0.10). In total, eight sequential sampling plans were designed and evaluated by comparing OC and ASN values. Besides that, comparison between different dispersion parameter of common *k* (K_c) and EILs were also evaluated. The best parameters (α and β) for developing Wald's SPRT plan were compared with conventional plan which used fixed sampling plan of 30 sample sizes in decision making using 6 independent samples. The comparison was based on economy obtained by the reduction of the sample number requested.

3.0 RESULTS AND DISCUSSION

The dispersion patterns of the CPB eggs on pod aged at 1 MBR and the parameter *k* for all the 9 samples were greater than zero which suggested that the CPB eggs found on pod aged 1 MBR were aggregated (Table 1). The goodness of fit test on the pooled data of 9 samples showed that the chi square value (26.16) was less than the critical value (26.22) at 1% significant level which indicated that the samples were fitted to the NBD. Therefore, the Wald's SPRT based on NBD distribution can be developed to monitor the CPB eggs population for making decision on spraying program.

Table 1 Dispersion pattern for CPB eggs on cocoa pod aged 1MBR in plot F55, CRDC Madai

Sampling time	N^a	Total CPB eggs	Mean, $\bar{x}$	Variance, s^2	*k*
1	17	19	1.12	1.24	10.62
2	12	25	2.08	3.36	3.41
3	29	88	3.03	7.53	2.05
4	27	116	4.30	25.06	0.89
5	33	64	1.94	5.68	1.01
6	16	37	2.31	5.70	1.57
7	25	30	1.20	3.50	0.63
8	21	67	3.19	6.66	2.93
9	26	62	2.38	8.49	0.93
Total	**206**	**508**	**2.47**	**8.83**	**0.958**
[b]Chi square value = 26.16ns (d.f. = 12)					

[a]Number of pods available at the specified pod length
[b]Chi square test on pooled data based on significant level of 1%

The common *k* (K_c) of the NBD was found to be 0.958 for 9 different samples. With this, the decision equations for Wald's SPRT in equations 3 to 6 were determined for different parameters of EILs, type I errors and type II errors which is shown in Table 2.

Table 2 The stop lines of Wald's SPRT for different parameters of EILs (0.5 and 1.0eggs/pod), type I error α and type II error β (0.05 and 0.10)

EIL	*A*	β	*S*	h_0	h_1
0.5	0.05	0.05	0.24	-5.31	5.31
		0.10	0.24	-4.06	5.21
	0.10	0.05	0.24	-5.21	4.06
		0.10	0.24	-3.96	3.96
1.0	0.05	0.05	0.47	-6.35	6.35
		0.10	0.47	-4.86	6.24
	0.10	0.05	0.47	-6.24	4.86
		0.10	0.47	-4.74	4.74

The stop lines using $\alpha = \beta = 0.05$ was slightly wider than other three stop lines while the stop lines using $\alpha = 0.10$ and $\beta = 0.10$ was narrow than other three stop lines (Tab. 2). In addition, the stop lines using $\alpha = 0.05$ and $\beta = 0.10$, was shifted above the stop lines using $\alpha = 0.10$ and $\beta = 0.05$ with equal width. Because of the mathematical properties of equations 3 to 6, varying the values α and β between 0.05 and 0.10 had a relatively small effect on the height of the stop lines and on the difference between the upper and lower lines within each pair (Fig.1A and 2A). However changing the values of α and β had a smaller effect on OC (Figure 1B and 2B) and ASN (Figure 1C and 2C) than changing the value of EIL.

When the value of EIL was changed from 0.5 to 1.0, it resulted in a shift of the OC to the right and a slight flattening of the OC at fixed values of α and β. This flattening is a sign of a reduction in the rate of correct decision. Furthermore, the ASN decreased with increasing EIL (Figure 1C and 2C). When a *K* value increased from 0.50 to 2.00, the stop lines became narrow while when an EIL increased from 0.50 to 1.00, the stop lines became more steep (Figure 3A). However changing the values of *K* had a smaller effect on OC (Figure 3B) but reduced the ASN when the *K* values increased (Figure 3C). Therefore, we selected $\alpha = \beta = 0.10$ to be used in developing the Wald's SPRT to monitor the cumulative number of CPB eggs per pod. Hence the decision boundaries of the Wald's SPRT under NBD with common K_c = 0.958 and EIL = 0.45 eggs/pod become;

$$\left.\begin{array}{l} D_i \leq -3.881 + 0.215n, \text{ stop and no insecticide spraying needed,} \\ D_i \geq \;\; 3.881 + 0.215n, \text{ stop and initiate the insecticide spraying} \end{array}\right\} \quad (7)$$

where D_i is the cumulative CPB eggs count till *i*th sample.

These two equations in (7) will be used to determine the upper and lower limits for any number of pod samples (Table 3). Five pods aged 1MBR per tree are drawn randomly in succession and the cumulative CPB eggs were compared with the lower limit (d_0) and upper limit (d_1) (Table 3). Sampling is to be continued till a point where in the cumulative CPB eggs fall either below d_0 or above d_1.

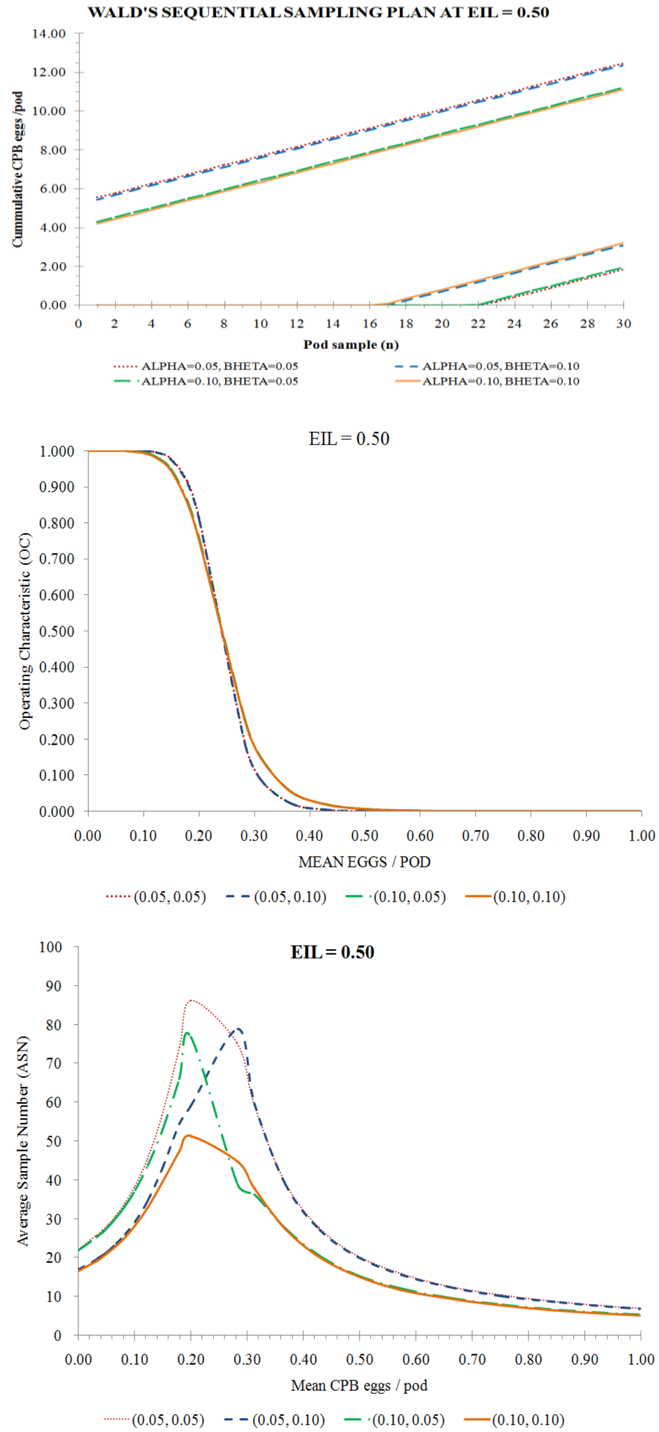


Figure 1 (A) Decision boundaries of the Wald's SPRT, (B) Operating characteristic (OC) curves and (C) Average sample number (ASN) curves for a Wald's SPRT of CPB eggs at different α (0.05 and 0.10) and β (0.05 and 0.10) for EIL (0.50)

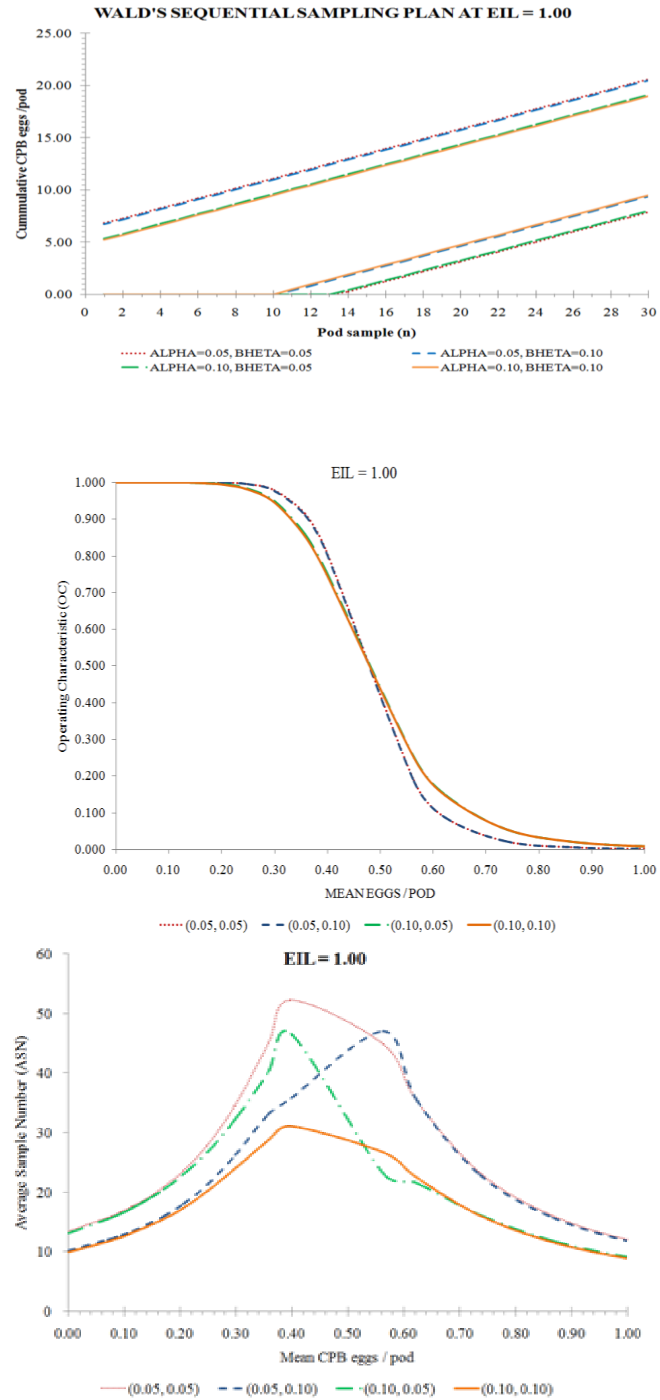


Figure 2 (A) Decision boundaries of the Wald's SPRT, (B) Operating characteristic (OC) curves and (C) Average sample number (ASN) curves for a Wald's SPRT of CPB eggs at different α (0.05 and 0.10) and β (0.05 and 0.10) for EIL (1.00)

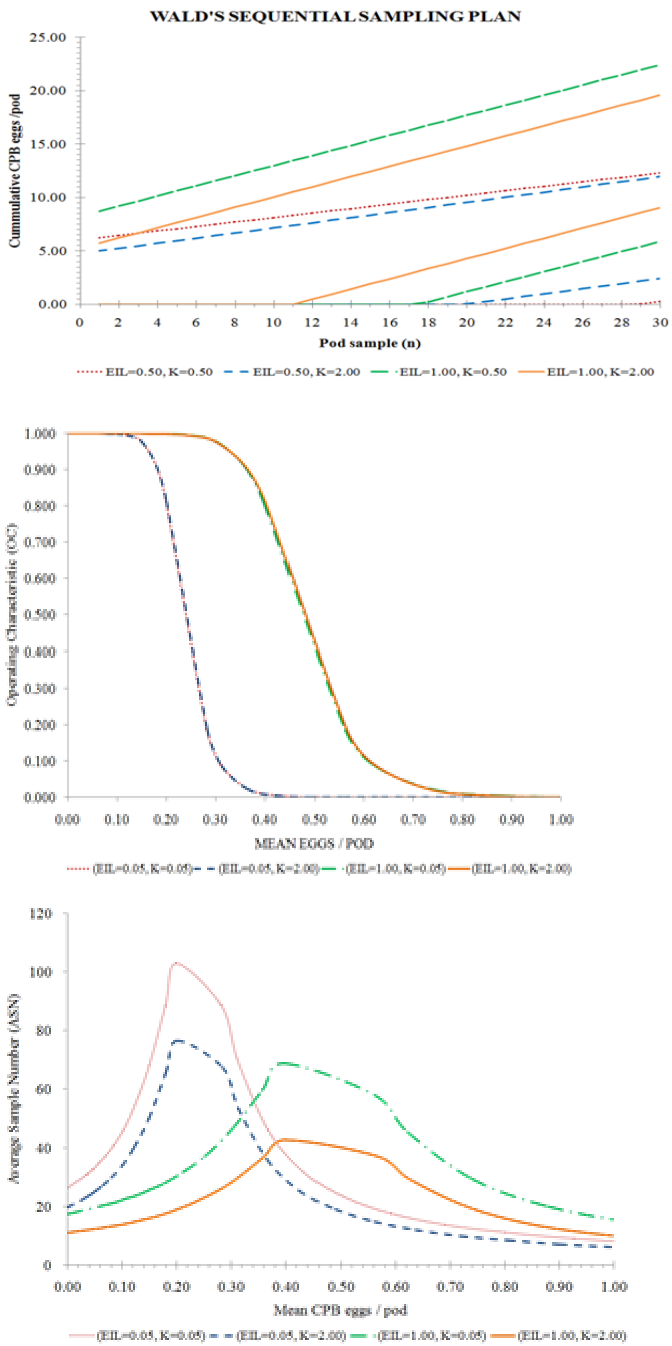


Figure 3 (A) Decision boundaries of the Wald's SPRT, (B) Operating characteristic (OC) curves and (C) Average sample number (ASN) curves for a Wald's SPRT of CPB eggs at α (0.10) and β (0.10) different EILs (0.50 and 1.0) and K values (0.50 and 2.00)

Table 3 Wald's SPRT table for treatment decisions

Sample number	Cumulative CPB eggs	
	Lower limit (d_0)*	Upper limit (d_1)
1	nd	4.08
2	nd	4.29
3	nd	4.51
4	nd	4.72
5	nd	4.94
6	nd	5.15
7	nd	5.37
8	nd	5.58
9	nd	5.80
10	nd	6.01
11	nd	6.22
12	nd	6.44
13	nd	6.65
14	nd	6.87
15	nd	7.08
16	nd	7.30
17	nd	7.51
18	0.01	7.73
19	0.22	7.94
20	0.44	8.16
21	0.65	8.37
22	0.87	8.59
23	1.08	8.80
24	1.30	9.02
25	1.51	9.23

*nd – No decision.

The Wald's SPRT required fewer samples to reach a decision compared to fixed sampling plan (n = 30 in Table 4). The Wald's SPRT showed a reduction of about 76.67% to 93.33% in the time spent in the sampling of CPB eggs compared with the fixed number of samples established for all the six samples. Fowler and Lynch (1987) showed that the Wald's SPRT only required an average of 40% to 60% as many samples as equally reliable fixed-sample-size methods.

Table 4 Comparison between the Wald's SPRT and fixed sampling plan based on the decision reached in 6 samples

Sampling time	Mean no. of CPB eggs per pod		Number of samples		Decision making		Economy (%)
	Fixed sampling plan	Wald's SPRT (0.1, 0.1)	Fixed sampling plan	Wald's SPRT (0.1, 0.1)	Fixed sampling plan	Wald's SPRT (0.1, 0.1)	
1	1.85	1.40	30	5	Control	Control	83.33
2	2.37	1.00	30	7	Control	Control	76.67
3	1.41	0.88	30	8	Control	Control	73.33
4	1.67	0.82	30	11	Control	Control	63.33
5	3.00	1.43	30	7	Control	Control	76.67
6	0.70	2.50	30	2	Control	Control	93.33

■4.0 CONCLUSION

The spatial distribution on CPB eggs population showed that the population was aggregated and followed the NBD pattern with a mean aggregation index (common *K*) value of 0.958. Furthermore, the decision-making sequential sampling plan based on Wald's SPRT developed in this study can be used in the Integrated Pest management (IPM) programmes in Malaysia to accurately decide on whether to initiate the insecticide spraying. The Wald's SPRT could save time and reduce cost of pesticide application because the control measure is only applied when necessary as determined by the plan.

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