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Sequential sampling plan for area-wide management of *Rhynchophorus ferrugineus* (Olivier) in date palm plantations of Saudi Arabia

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Abstract. A decision-making sampling plan was developed to initiate new and validate ongoing area-wide red palm weevil *Rhynchophorus ferrugineus* (Olivier) integrated pest management (IPM) programmes in date palm plantations of Saudi Arabia based on the concept of sequential sampling. Spatial distribution studies revealed that *R. ferrugineus* population was aggregated and followed the negative binomial series with a mean aggregation index (common *K*) value of 3.56. In the sampling plan developed, young date palms are inspected in a sequence in units of 100 palms (1 ha) until an accurate decision on the infestation level can be made. The plan rates infestations as low and high if $d_0 \leq 0.478n - 7.519$ and $d_1 \geq 0.478n + 7.519$, respectively, where d_0 and d_1 are the cumulative maximum and minimum infested palms per ha (100 young palms) for not recommending and recommending area-wide management of *R. ferrugineus*, respectively, and *n* is the area sampled in ha. In this sampling plan, if 100 palms are inspected and eight or more infestations are detected, then area-wide *R. ferrugineus* IPM is required. On a 100 ha scale (10,000 palms) the plan becomes stricter and permits only 55 infestations.

Key words: date palm, red palm weevil, spatial distribution, sequential sampling, *Rhynchophorus ferrugineus*, IPM

Introduction

Red palm weevil (RPW) *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Curculionidae/Rhynchophoridae/Dryopthotidae) is a key pest of several palm species and is reported from nearly 50% of the date palm *Phoenix dactylifera* L. (Arecaceae) growing countries (Faleiro, 2006). Ever since *R. ferrugineus* was reported from Rass-El-Khaima in the United Arab Emirates in 1985, it has spread rapidly to all the countries of the Gulf region in the Middle East infesting approximately 5% of the palms in the region with an annual infestation rate of about 1.9 (Zaid *et al.*, 2002). Saudi Arabia produces nearly a million tonnes of dates annually accounting for 15% of the global date production (available at: http://en.wikipedia.org/wiki/Date_(fruit)#Fruit). With the synthesis of the male-produced *R. ferrugineus* aggregation pheromone (4-methyl-5-nonanol) in the early 1990s (Hallett *et al.*, 1993) and its subsequent commercial availability, pheromone-based area-wide *R. ferrugineus* integrated pest management (IPM) programmes were initiated to suppress this pest in several date palm plantations of Saudi Arabia and other Gulf countries of the Middle East (El-Ezaby *et al.*, 1998; Abraham *et al.*,

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2000; Vidyasagar *et al.*, 2000; Al-Khatri, 2004; Oehlschlager, 2005).

Adult *R. ferrugineus* female weevils usually prefer to infest young palms, and hence, as new date palm plantations are developed in the Gulf region, the threat of *R. ferrugineus* attacking these groves always exists. Recent reports suggest that the annual loss due to eradication of severely infested palms by *R. ferrugineus* in Saudi Arabia has been estimated to range from US$1.74 to 8.69 million at 1–5% infestation, respectively (El-Sabea *et al.*, 2009). The concealed nature of this pest demands that a constant vigil be kept on its activity. Early detection of infestation due to *R. ferrugineus* is the key to the success of any strategy aimed to manage this lethal pest. As there is no reliable instrument to detect infested palms in the field, checking teams have to inspect every palm and rely only on their experience to locate *R. ferrugineus*-infested date palms. An assumed action threshold of 1% infested palms has been recommended previously to implement pheromone-based area-wide *R. ferrugineus* IPM programmes (Faleiro, 2006).

Relying only on infestation reports or pheromone trap captures to initiate area-wide *R. ferrugineus* IPM operations could often result in either an over- or underestimation of the pest intensity in the field. Such a decision would either lead to initiating IPM when it is not required or not implementing the programme when necessary. Several *R. ferrugineus* IPM programmes have been in progress for the last 15 years in Saudi Arabia, and it is necessary to periodically validate these programmes.

For the purpose of IPM decision making, the concept of sequential sampling has been reported several times since the mid-1950s (Morris, 1954; Harcourt, 1966; Smith and Shepard, 2004). Although Faleiro and Ashok Kumar (2008) have developed such sampling plans for managing *R. ferrugineus* in coconut plantations of India, there are no reports on decision-making sampling plans for the management of this pest in date palm.

We have therefore studied the spatial distribution of *R. ferrugineus* in the region and developed a decision-making sampling plan for the management of *R. ferrugineus* in date plantations of Saudi Arabia, using the concept of sequential sampling.

Materials and methods

The first step in the development of a sequential sampling plan is to establish the spatial distribution of the insect in nature (Morris, 1954). Although *R. ferrugineus* infestation pattern in date plantations of Al Hassa, Saudi Arabia, depicts clumped or aggregated distribution (Anonymous, 1998), there is no information on the extent of clumping of the weevil population based on mathematical tests in date plantations.

To ascertain the spatial distribution of *R. ferrugineus*, 120 date plantations including 41,100 palms were inspected in Al Hassa, Saudi Arabia, for 4 days from 4 to 7 August 2008. Data on % infestation for each of the 4 days were used to compute (i) mean and variance, and (ii) clumping parameter K by determining the moment estimate of K and common K values as suggested by Southwood (1978).

(i) *Mean–variance test*: here, mean ($\bar{x}$) and variance (S^2) were determined for % infestation, and compared for each of the 4 days. When $S^2 < \bar{x}$, the distribution of the population is uniform, and when $S^2 > \bar{x}$, it indicates aggregation. When $S^2 = \bar{x}$, it indicates random or Poisson distribution.

(ii) *Dispersion parameter ‘K’:* clumping or dispersion parameter K was determined by the following methods:

(a) Moment estimate of K: this parameter measures the degree of aggregation (Elliott, 1979) and was computed using the following formula:

$$K = \bar{x}^2/(S^2 - \bar{x}).$$

(b) Clumping parameter K: this is a valid and readily computed measure of aggregation for a wide range of insect counts (Bliss and Owen, 1958; Waters, 1959). Here, common K (K_c) value was computed using the moment and regression method of Bliss and Owen (1958), where

$$K_c = (\bar{x})^2 - (S^2/N)/S^2 - \bar{x}.$$

For the above K estimates, a value of <8 indicates clumped or aggregated distribution, while a value of >8 suggests random distribution.

Having studied the distribution pattern of *R. ferrugineus* population, the next step was to develop a decision-making sampling plan for initiating new and validating ongoing *R. ferrugineus* IPM programmes. In this study, we devised a decision-making sequential sampling plan based on (i) the null hypothesis that ‘area-wide *R. ferrugineus* IPM is not required’, (ii) a mean aggregation index (K_c) value of 3.56 and (iii) an assumed action threshold of 1% infested palms. Furthermore, the sampling plan was developed at a risk factor of α and β set at 0.01, where α is the probability of recommending area-wide management when it is not required, and β is the probability of failing to recommend area-wide management when it is required.

The acceptance and rejection lines of the hypothesis that ‘area-wide *R. ferrugineus* IPM is not required’ are based on the sequential probability ratio test formulae outlined by Wald (1947), and were devised using the formulae:

$$d_0 = S_n + h_0 \text{ and } d_1 = S_n + h_1,$$

where d_0 and d_1 are the cumulative maximum and minimum infested palms per ha (100 young palms < 20 years old) for not recommending and recommending area–wide management of *R. ferrugineus*, respectively, and n is the area sampled in ha. Commercial date plantations in Saudi Arabia use a plant spacing of 10×10 m accommodating 100 palms/ha. As RPW usually attacks young date palms below the age of 20 years (Abraham *et al.*, 1998; Anonymous, 1998), the number of palms sampled/inspected in the susceptible age group is important rather than the area covered.

$$S = \text{slope} = K[\log(q_1/q_0)/\log(p_1q_0/p_0q_1)],$$

where K is the index of aggregation; $p_0 = m_0/\mathrm{K}$; $p_1 = m_1/K$; $q_0 = p_0 + 1$ and $q_1 = p_1 + 1$ and m_0 and m_1 are the lower and upper levels of the infestation set at 1/3 and 2/3 of the assumed action threshold levels. Stern *et al.* (1959) reported that the economic threshold value would correspond to m_1, which is the level at which treatment should be initiated to prevent economic loss. h_0 is the intercept of the lower line and h_1 is the intercept of the upper line, and are given by $h_0 = \log B/\log(p_1q_0/p_0q_1)$, where $B = \beta/1 - \alpha$, and $h_1 = \log A/\log(p_1q_0/p_0q_1)$, where $A = 1 - \beta/\alpha$, and α and β are the probabilities of failing to recommend the correct decision (i.e. implementing and rejecting area-wide management when it is not essential and essential, respectively) which was set at 0.01 in the plan.

Having developed the sequential sampling plan, it is essential to ascertain its performance. The operating characteristic (OC) and the average sample number (ASN) curves are helpful in visualizing the performance of a sequential sampling plan. A two-level classification plan as the one envisaged in this study is assessed by two basic criteria: (i) accuracy of the classification and (ii) how rapidly an accurate decision is made. These questions are answered by the OC and ASN curves (Binns and Nyrop, 1992; Binns *et al.*, 2000).

These curves are based on the formulae outlined for negative binomial distribution by Oakland (1950) and Waters (1955). The OC curve was developed using the formula:

$$L(p) = A^h - 1/A^h - B^h,$$

where A and B are as defined earlier and h is the dummy variable, while

$$p = 1 - (q_0/q_1)^h/(p_1q_0/p_0q_1)^h - 1.$$

The ASN curve developed for the plan in this study indicates the number of samples at different infestation levels and is given by

$$E_p(n) = h_1 + (h_0 - h_1)L(p)/K_p - S,$$

where h_1, h_0, $L(p)$, K, p and S are as defined earlier.

The spatial distribution tests, sequential sampling plan and the OC and ASN curves in this study were computed through web-based software available at http://icargoa.res.in/nbd.

Results

Data presented on spatial distribution studies in Table 1 reveal that the variance was more than the mean for all the 4 days, indicating aggregation of the pest. Furthermore, the moment estimate of K and common K values computed for each of the 4 days were <8, indicating aggregation or contagious distribution of *R. ferrugineus* in date plantations of Al Hassa, Saudi Arabia (Table 1). The common K value varied from 2.04 to 4.99, from which a mean common K value of 3.56 was computed as the aggregation index of the pest.

Incorporating the above distribution of *R. ferrugineus* in date plantations of the region (common K value of 3.56), decision-making sampling lines to accept and reject the null hypothesis that 'area-wide *R. ferrugineus* IPM is not required' were computed as $d_0 = 0.478n - 7.519$

Table 1. Spatial distribution parameters of *Rhynchophorus ferrugineus* in date plantations of Al Hassa, Saudi Arabia (2008)[+]

	Day 1	Day 2	Day 3	Day 4
Number of observations in sample	30 plantations (11,865 palms)	30 plantations (9300 palms)	30 plantations (10,235 palms)	30 plantations (9700 palms)
Mean	1.828	2.087	1.275	1.270
Variance	3.087	4.148	1.613	1.583
Moment estimate of 'K'	2.655	2.112	4.803	5.166
Common 'K'	2.574	2.045	4.644	4.998

[+] Degree of aggregation/clumping is represented by K. For the above K estimates, a value of less than 8 indicates clumped or aggregated distribution.

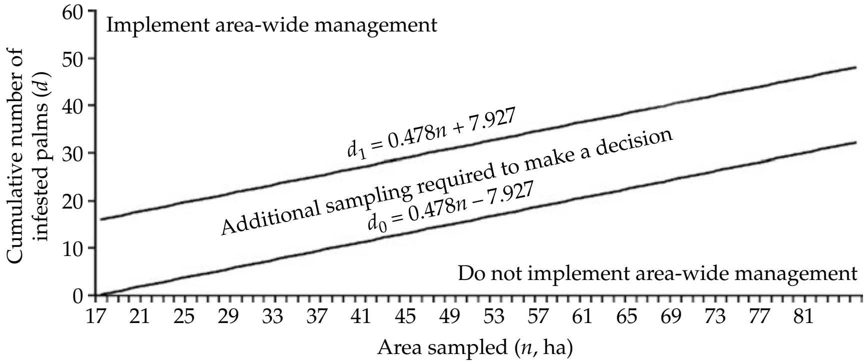

Fig. 1. Sequential sampling plan for area-wide management of *Rhynchophorus ferrugineus* in date plantations of Saudi Arabia

and $d_1 = 0.478n + 7.519$, respectively, where d_0, d_1 and n are as defined above (Fig. 1). So as to facilitate the use of the sampling plan in the field, we developed Table 2 as a ready-to-use decision-making guide for the plan at the above-mentioned risk factor for the lower and upper infestation limits at different sample sizes.

The OC curve for the plan presented in Fig. 2 suggests that at lower infestation means, the probability of accepting the null hypothesis and not implementing area-wide *R. ferrugineus* IPM is high, with the reverse being true at high infestation means indicating that the sampling plan devised is accurate. In addition, the ASN curve for the plan suggests that at low and high infestation means, few samples are needed, while at medium infestation means, more samples are required, which is also in agreement with the concept of sequential sampling. As per the ASN curve for the plan developed, the maximum sample size is 79 (Fig. 2).

Discussion

Spatial distribution

Understanding the spatial distribution of an insect pest is an important prerequisite for developing sequential sampling plans (Waters, 1955). Spatial distribution patterns of a population can deviate from randomness to be either uniform or clumped (Ruesink and Kogan, 1974). The significance of incorporating the spatial and temporal dimensions in managing mobile pests has been well documented in the literature (Yu and Leung, 2006).

In this context, the relationship between variance and mean is extremely useful and allows the development of sequential sampling procedures (Binns and Nyrop, 1992). In this study, the variance exceeded the mean, suggesting that the population is aggregated and follows the negative binomial distribution pattern (Southwood, 1978). Furthermore, the dispersion parameter (moment estimate of K and common K) values were < 8. This also indicates aggregation according to Southwood (1978). This type of aggregation in a *R. ferrugineus* population has been cited as a cause of increasing in clusters of infestations in date palm plantations in the Al Hassa oasis in Saudi Arabia, resulting in spread of the pest in and around heavily infested date plantations where severely infested palms were eradicated (Anonymous, 1998). Similar studies involving a series of mathematical tests on monthly weevil captures using food-baited RPW pheromone traps showed that its population was highly aggregated in coconut plantations of India (Faleiro *et al.*, 2002). Mass trapping of *R. ferrugineus* in an area-wide operation in coconut plantations of India over a period of 18 months in two villages brought down infestation levels below the assumed action threshold of 1% infestation (Sujatha *et al.*, 2006).

Sequential sampling plan

Having studied the distribution pattern of *R. ferrugineus* on date palm in Al Hassa oasis, we incorporated the aggregation index (mean common K) value of 3.56, and devised a decision-making sampling plan to initiate and validate *R. ferrugineus* IPM in date plantations of Saudi Arabia.

Initiating R. ferrugineus *IPM*

In this plan, the upper limit to implement area-wide *R. ferrugineus* IPM for the first 100 palms inspected is eight infested palms. Additional sampling would have to be done at an infestation level of < 8 infested palms (Table 2). In the plan developed, infestation could be rated as low and high if $d_0 \leq 0.478n - 7.519$ and $d_1 \geq 0.478n + 7.519$, respectively. Infestation above d_0 and below d_1 would be rated as medium at which no decision can be made, and additional sampling would be needed

Table 2. Decision-making sequential sampling table to initiate and validate area-wide management of *Rhynchophorus ferrugineus* in date plantations of Saudi Arabia (2010)

		Cumulative number of infested palms (risk factor: 0.01)				Cumulative number of infested palms (risk factor: 0.01)	
Sample number	No. of palms sampled	Lower limit	Upper limit	Sample number	No. of palms sampled	Lower limit	Upper limit
1	100	ND+	8	51	5100	17	32
2	200	ND	8	52	5200	17	32
3	300	ND	9	53	5300	18	33
4	400	ND	9	54	5400	18	33
5	500	ND	10	55	5500	19	34
6	600	ND	10	56	5600	19	34
7	700	ND	11	57	5700	20	35
8	800	ND	11	58	5800	20	35
9	900	ND	12	59	5900	21	36
10	1000	ND	12	60	6000	21	36
11	1100	ND	13	61	6100	22	37
12	1200	ND	13	62	6200	22	37
13	1300	ND	14	63	6300	23	38
14	1400	ND	14	64	6400	23	38
15	1500	ND	15	65	6500	24	39
16	1600	0	15	66	6600	24	39
17	1700	1	16	67	6700	25	40
18	1800	1	16	68	6800	25	40
19	1900	2	17	69	6900	26	41
20	2000	2	17	70	7000	26	41
21	2100	3	18	71	7100	26	42
22	2200	3	18	72	7200	27	42
23	2300	3	19	73	7300	27	42
24	2400	4	19	74	7400	28	43
25	2500	4	19	75	7500	28	43
26	2600	5	20	76	7600	29	44
27	2700	5	20	77	7700	29	44
28	2800	6	21	78	7800	30	45
29	2900	6	21	79	7900	30	45
30	3000	7	22	80	8000	31	46
31	3100	7	22	81	8100	31	46
32	3200	8	23	82	8200	32	47
33	3300	8	23	83	8300	32	47
34	3400	9	24	84	8400	33	48
35	3500	9	24	85	8500	33	48
36	3600	10	25	86	8600	34	49
37	3700	10	25	87	8700	34	49
38	3800	11	26	88	8800	35	50
39	3900	11	26	89	8900	35	50
40	4000	12	27	90	9000	36	51
41	4100	12	27	91	9100	36	51
42	4200	13	28	92	9200	37	52
43	4300	13	28	93	9300	37	52
44	4400	14	29	94	9400	37	53
45	4500	14	29	95	9500	38	53
46	4600	14	30	96	9600	38	53
47	4700	15	30	97	9700	39	54
48	4800	15	30	98	9800	39	54
49	4900	16	31	99	9900	40	55
50	5000	16	31	100	10,000	40	55

+ND, no decision.

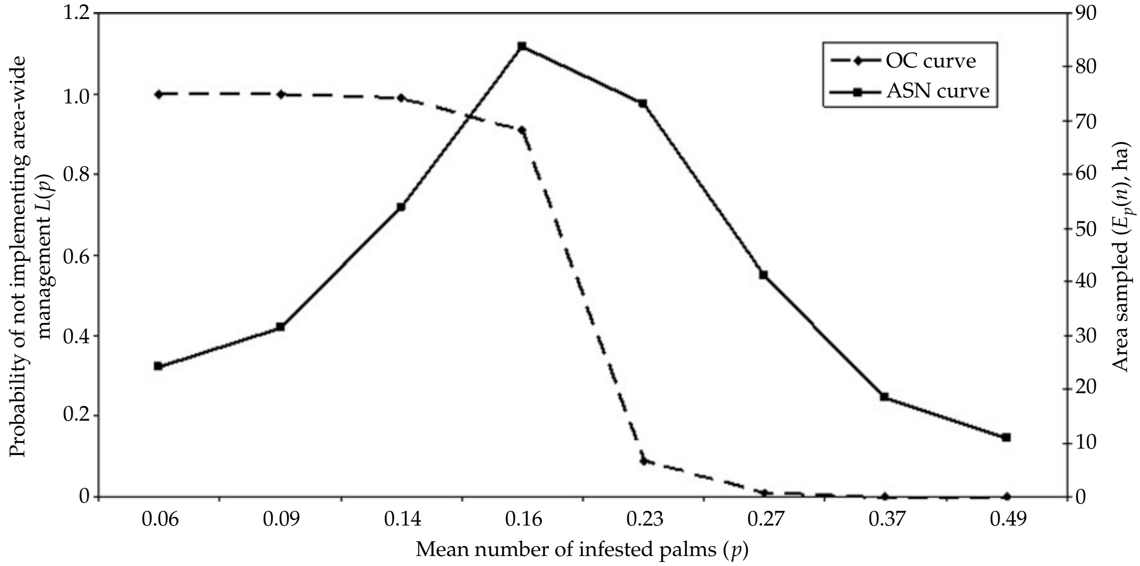

Fig. 2. Operating characteristic (OC) and average sample number (ASN) curves for the sequential sampling plan

to initiate *R. ferrugineus* IPM. Table 2 is proposed as a ready-to-use decision-making guide, wherein the cumulative total of infestations less than or equal to the lower limit implies that the infestation is light and there is no need to implement area-wide management of *R. ferrugineus*. A cumulative total of more than or equal to the upper limit indicates that the infestation is high and area-wide management of *R. ferrugineus* is essential. To apply this plan in the field, running totals of infestation counts are tallied against the lower and upper infestation limits after every 100th palm inspected, and a decision either to implement and not to implement area-wide *R. ferrugineus* IPM or to continue sampling is made. In Saudi Arabia, RPW infestations gradually increase from the month of May reaching a peak in November, before declining during the winter (Anonymous, 1998). The sampling plan developed in this study could be effectively used to arrive at an accurate decision on damage levels throughout the year at both high and low damage levels.

Faleiro and Ashok Kumar (2008) developed two sequential sampling plans to manage *R. ferrugineus* in coconut plantations of India based on a common aggregation index value of 3.45, and assumed action threshold values of either 1 or 0.5% infested palms, and a risk factor of making the wrong decision was set at 0.05. In the present study, we developed the sampling plan at a very low risk factor (0.01), as date palm has a much higher monitory value when compared with coconut. Besides, the damage due to *R. ferrugineus* in date palm is more difficult to detect when compared with coconut. Hence the error of making a wrong decision is set at only 1 in 100 in this study when compared with 5 in 100 to manage *R. ferrugineus* in coconut (Faleiro and Ashok Kumar, 2008).

Since the 1950s, several decision-making sampling plans for extending threshold-based pest management to the field on the concept of sequential sampling have been developed to manage insect pests in diverse ecosystems including forest insects (Waters, 1955), cabbage worm (Harcourt, 1966), cotton fleahopper (Pieters and Sterling, 1974), rice planthoppers (Shepard *et al.*, 1986) and cotton bollworms (Beyo *et al.*, 2004).

Validating R. ferrugineus *IPM*

Pheromone-based area-wide *R. ferrugineus* IPM programmes that have been in progress in Saudi Arabia since 1994 need to be validated periodically. Currently, the performance of *R. ferrugineus* IPM programmes is gauged on the basis of infestation reports and pheromone trap capture data, without considering the spatial distribution of this pest and the risk of either over- or underestimating the damage intensity. This could mislead pest managers to continue with *R. ferrugineus* IPM in areas where it is not required or stop/scale down the operation where it is essential. We recommend the use of this plan to validate ongoing *R. ferrugineus* IPM programmes in date plantations of Saudi Arabia, which is devised at a low risk factor (0.01) of making the wrong decision. Hence by using this plan, if repeatedly $d_0 \leq 0.478n - 7.519$, then the strategy adopted in that particular operational area could be rated as effective, and the entire operation could be scaled down and valuable resources diverted to localities where the pest is severe. On the other hand, if persistently

$d_1 \geq 0.478n + 7.519$, then the IPM programme in that particular area needs to be strengthened by adopting one or several of the *R. ferrugineus* IPM tactics proposed by Abraham *et al.* (1998) of either repeatedly inspecting palms to detect infestations around pheromone traps with high weevil captures, conducting preventive cover sprays with insecticides, especially in endemic pockets around palms that are heavily infested and had to be eradicated, intensifying the search to locate hidden breeding sites of the pest (beheaded palms, closed and neglected gardens) or strengthening quarantine regimes to prevent its reintroduction where *R. ferrugineus* has been controlled. At infestation levels between d_0 and d_1, the intensity of the pest could be rated as medium, warranting the need to continue with the programme, which should be strengthened to bring the infestation below the lower limit. At such persisting levels of moderate infestation, it would be reasonable to infer that although the strategy is working, it is not having the desired effect and infestation could cross the upper limit at any moment. Hence at medium infestation levels, no decision can be made, and the next unit of 100 palms would have to be inspected for the purpose of validating ongoing programmes. Under this scenario, it would be desirable to strengthen the IPM strategy in areas with medium infestation. Faleiro and Ashok Kumar (2008) developed similar sampling plans to validate *R. ferrugineus* IPM programmes in coconut plantations of India.

The ongoing area-wide *R. ferrugineus* IPM programmes in Saudi Arabia are substantially or fully subsidized by the government with very little farmer participation. Yu and Leung (2006) have developed a model to demonstrate that for managing a common mobile pest faced by many heterogeneous farmers, area-wide pest management is superior to farm-by-farm control, and that co-operation of these heterogeneous farmers is crucial for the success of area-wide pest management. In the date growing oasis of Al Hassa in Saudi Arabia, farmer participation in a 250 ha date plantation situated in an *R. ferrugineus* hot spot involving regular inspection of palms, weekly servicing of pheromone traps to ensure strong bait–lure synergy, coupled with localized preventive insecticidal cover treatments around pheromone traps capturing weevils, resulted in significant reduction in infestation. Hence farmer participatory *R. ferrugineus* IPM is highly recommended (Faleiro, 2008) in the fight against this dreaded pest.

OC and ASN curves

The OC and ASN curves do not directly assist in devising a sequential sampling plan, but are essential to visualize the accuracy and performance of the plan developed (Harcourt, 1966; Binns and Nyrop, 1992). Here, the OC curve predicts the probability of not implementing area-wide management of *R. ferrugineus* at different infestation means. For the plan developed in this study, the probability of not implementing area-wide *R. ferrugineus* IPM at low infestation means is high, while as the infestation increases, the probability of accepting the null hypothesis and not implementing area-wide *R. ferrugineus* IPM is low. This is in accordance with the simulation model provided by Binns *et al.* (2000) (available at http://www.nysaes.cornell.edu/ent/faculty/nyrop/cpdm), which suggests that a perfect OC curve has a horizontal line followed by a vertical drop with a subsequent horizontal line at low, medium and high infestation means, respectively, as seen in Fig. 2 of this study.

Furthermore, the ASN curve indicates sampling requirement at different infestation levels. At low and high infestation means, only a few samples are needed to arrive at the correct decision, while at medium infestation levels, more samples are required (Fig. 2), which is in agreement with the concept of sequential sampling. This therefore suggests that the sampling plan developed is accurate. Beyo *et al.* (2004) showed that the ASN curve developed for sampling of three cotton bollworms in Northern Cameroon attained a maximum of 17 plants, and was little affected by fluctuations in the clumping index *K*.

At medium levels of infestation, the problem of continuous open-ended sampling is often encountered while using sequential sampling plans (Ruesink and Kogan, 1974). Hence we propose that the maximum number of samples derived in the ASN curve of this study (79) could be taken as the point at which sampling should be stopped, and a decision to initiate IPM should be taken. For validating *R. ferrugineus* IPM programmes, this problem would not arise.

Conclusion

Spatial distribution studies based on infestation reports in the Al Hassa date palm oasis of Saudi Arabia revealed that the population was clumped and followed the negative binomial distribution pattern with a mean aggregation index (common *K*) value of 3.56. Furthermore, the decision-making sequential sampling plan developed in this study will assist area-wide *R. ferrugineus* IPM programmes in Saudi Arabia to accurately decide on whether to initiate new area-wide programmes. Besides, the plan provides pest managers with a valuable tool to validate ongoing area-wide *R. ferrugineus* IPM programmes and will go a long way in optimizing resources in the fight against this pest in Saudi Arabia.

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