Sequential Sampling Plans for Use in Timing Insecticide Applications for Control of European Corn Borer (Lepidoptera: Pyralidae) in Potato

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ABSTRACT Sequential sampling plans were developed for use in recommending control of European corn borer, *Ostrinia nubilalis* (Hübner), in potato, *Solanum tuberosum* L., fields based on the distribution of damaged stems. Likelihood ratio tests indicated that the beta-binomial distribution (aggregated) provided a better fit than the binomial (random) when the mean percentage of damaged stems in a field was ≥6%, but not when damage was <6%. Similarly, variance-ratio (D) and C(α) tests indicated that damage was aggregated generally at damage levels ≥6%. Because the slope (b) ± SEM of the binary form of the Taylor power law (1.15 ± 0.05) (total of 41 fields) revealed moderate overdispersion, and a weak linear relationship existed between the index of aggregation (θ) and p, sequential sampling plans were evaluated under various degrees of aggregation. The precision and practicality of the sequential sampling plans were evaluated through calculation of operational characteristic and average sample number functions for both simulated binomial and beta-binomial distributions. Precision of the sequential sampling plans decreased as the aggregation of *O. nubilalis* damage increased, especially when the proportion of damaged stems was near threshold. However, precision increased dramatically if fields near threshold were sampled more than once. Because, in practice, potato fields near threshold are sampled repeatedly, the sampling plans were considered acceptable. A comparison between the sequential sampling plan and the conventional sampling plan revealed that control decisions made using the sequential plan agreed closely with those made by the conventional plan, and averaged 57% fewer samples needed to make the decision.

KEY WORDS presence-absence sampling, binomial and beta-binomial probability distributions, action thresholds, decision making

IRISH POTATO, *Solanum tuberosum* L., fields in eastern North Carolina are infested annually by 1st-generation larvae of European corn borer, *Ostrinia nubilalis* (Hübner), in early May (Kennedy and Anderson 1981). *O. nubilalis* larvae damage potato by tunneling near the base of stems causing breakage and lodging during late May and early June when the potato crop is in the late bloom to postbloom stages. Because most of the potato acreage is harvested in June before a damaging 2nd generation of *O. nubilalis* develops, potato growers manage only the 1st generation.

Growers average of 1–2 insecticide applications to manage *O. nubilalis* infestations in potato in eastern North Carolina (Toth 1995). Scouting for damage in potato is initiated when adult activity is high, when ≥30 moths are captured in light traps over 5 consecutive days (Averre and Sorensen 1979). Damage assessment is based on a presence-absence classification because it is nondestructive and easier than determining the number of larvae within the plant. Crop consultants in North Carolina generally recommend an insecticide application when ≥10% of the stems show evidence of tunneling by *O. nubilalis* larvae. Nault and Kennedy (1996) have shown recently that damaging *O. nubilalis* infestations in potato can be managed effectively using 1 well-timed application of either carbofuran or methamidophos applied when 20–40% of the stems show evidence of tunneling. Because most growers use these insecticides to control *O. nubilalis* damage in potato, a 30% damaged stems threshold has been recommended (Nault and Sorensen 1996). Currently, scouts use a sampling plan that requires the inspection of 100 potato stems (10 sites × 10 stems per site) in an 18- to 30-ha area.

Sequential sampling plans, which are typically more precise and time efficient than fixed-sample-size sampling plans, could facilitate scouting for *O. nubilalis* in potato. The development and evaluation of a sequential sampling plan requires knowledge of the spatial distribution of the target pest or its damage. In the case of *O. nubilalis,* field scouts use the incidence of *O. nubilalis* damaged stems as an index of the infestation level, and the spatial distribution of tunneled stems in potato fields is unknown. Because damage is assessed in a binary nature (i.e., stem is damaged or not damaged), and binary data have a different variance-mean structure than enumerative data (Madden and Hughes 1995), the incidence of damaged stems may not be appropriately described by the Poisson, negative binomial and related distributions (Hughes and Madden 1992, 1993). These distributions could be used to appropriately fit binary data only in cases when mean damage levels are 20% or less (Madden and Hughes 1995). Levels of *O. nubilalis* damage in North Carolina potato fields often exceed 20%. Therefore, probability distributions such as the binomial and beta-binomial models, which are most appropriate for describing binary data that are random or aggregated, respectively, were chosen to describe the distribution of *O. nubilalis* in potato fields.

This study was undertaken to identify the distribution of *O. nubilalis* damage within potato fields and to develop sequential sampling plans using different action thresholds (i.e., 10 and 30% damaged stems) to aid in timing insecticide applications for managing *O. nubilalis* damage. Sequential sampling plans were evaluated by the following: operational characteristic and average sample number computer simulations, comparing the control decisions made by the sequential plan with the conventional sampling plan, and comparing the average number of samples required to make a control decision using the sequential plan with the conventional plan.

Materials and Methods

Data Collection. In total, 41 commercial potato fields in 5 counties in eastern North Carolina were sampled in either May or June. The number of fields sampled within each county were as follows: Carteret (1), Pamlico (6), Pasquotank (13), Perquimans (2), and Washington (19). The year and number of fields sampled within each year were as follows: 1991 (8), 1992 (6), 1993 (19), and 1994 (8). Although the cultivar of potato was not recorded in each field, most hectares are planted with either 'Atlantic' or 'Superior' (≈85% of total), and our experience is that both cultivars are equally preferred by *O. nubilalis*. Conventional commercial production practices were implemented in all fields.

Twenty sites (site = sampling unit) (N = 20) were sampled within each field in a systematic bow-tie progression pattern. These sites were sampled within a 1-ha portion of the field. One-half of these sites were sampled within the first 2–5 rows, which were adjacent to a field edge that was parallel with rows (i.e., 5 sites from each side of the field). Field edges typically were demarcated by a drainage ditch, canal, road, or hedge row of trees. Sites near field edges were separated by at least 45 m. The remaining 10 sites sampled were separated across rows by 5–10 m and within rows by 30 m. In total, 10 stems (n = 10) were sampled successively within each site (total = 200 stems per field). Stems were recorded as damaged or not damaged based on the presence or absence of at least 1 *O. nubilalis* entry hole. Entry holes made by 1st or 2nd instars were typically at the proximal end of the compound leaf or on the stem near the proximal end of the leaf. Holes made by late instars were typically near the base of stems.

Spatial Distribution Determination. *Probability Model Comparison.* Binomial and beta-binomial distributions are both discrete probability distributions that are appropriate for describing binary data (Madden and Hughes 1995). If the pattern of damaged plants within a field is random, the probability distribution is classified as a binomial, which can be represented as the probability of damaged stems in a site as:

$$\Pr(X = x) = (n!/[n - x]!\,x!)\,(p^x[1 - p]^n - x) \quad (1)$$

where each observation is independent, X is the random variable for damaged stems in a site, x is a specific value of X (0, 1, . . .), n is the number of stems examined in a site, and the true proportion of damaged stems is p (an unknown parameter to be estimated) (Hughes and Madden 1993). The expectation of X is np and the variance is $np(1 - p)$. In contrast, if the pattern of damaged plants within a field is aggregated, the appropriate probability distribution is the beta-binomial (Hughes and Madden 1993), which can be written as:

$$\Pr(X = x) = (n!/[n - x]!\,x!) \cdot (B[\alpha + x, n + \beta - x]/B[\alpha,\beta]) \quad (2)$$

where $B(.,.)$ is the beta function, and α and β are parameters to be estimated. Furthermore, α and β can be written as:

$$\alpha = p/\Theta,\ \beta = (1 - p)/\Theta \quad (3)$$

where θ (an index of aggregation) is the measure of the heterogeneity of damaged stems. Here, p represents the expected proportion damaged. As θ approaches 0 the beta-binomial reduces to the binomial, and as θ increases aggregation increases. For the purpose of calculating the parameters p and θ, the moment estimates are as follows:

$$p = m/n \quad (4)$$

where m is the estimated mean of X, and

$$\Theta = (s^2 - np[1 - p])/(n^2p[1 - p] - s^2) \quad (5)$$

where s^2 is the calculated variance of X for the N sites per field.

Maximum likelihood estimates of p and θ from each field, using the moment estimates as initial values, were determined using the computer program BBD written by Madden and Hughes (1994). This program was developed for fitting and comparing the binomial and beta-binomial distributions, following methods described by Press et al. (1986) and Skellam (1948), respectively. BBD calculated the expected values for each distribution and then compared the goodness-of-fit between the observed frequency and the expected frequency of each distribution using a chi-square test at a significance level calculated using the method by Gates and Ethridge (1970). A low chi-square statistic and a high probability value (e.g., >0.05) indicated that the specified distribution was appropriate. Alternatively, a high chi-square statistic and a low probability value suggested that the specified distribution was not appropriate. All expected values below 5 were pooled into 1 frequency class to ensure a conservative chi-square test. A single-degree-of-freedom likelihood ratio (chi-square) test was used to determine if the beta-binomial distribution provided a significantly better fit to the data than the binomial, as discussed by Williams (1975).

Standard errors of the estimated parameter (θ) were calculated as described by Madden and Hughes (1994). A t-test was not conducted to determine if θ was significantly different from 0 because this test can be overly conservative in detecting departures of θ from 0 when N is relatively low (N for each field = 20) (Johnson et al. 1992). The relationship between (θ) and p was described using simple linear regression analysis using the procedure PROC GLM (SAS Institute 1990). A significant linear relationship would indicate that aggregation increases as the incidence of damaged plants increases, indicating that the precision and performance of the sequential sampling plan should be evaluated over a range of aggregation values (θ).

Variance-Ratio Test. The index of dispersion (D) was calculated by the ratio of the observed calculated variance to the theoretical variance for a binomial (random) distribution (Fisher 1970). The equation can be written as:

$$D = s^2/(np[1 - p]) \qquad (6)$$

where $np(1 - p)$ is the variance of the binomial distribution. A chi-square test, where the test statistic is $(N - 1)D$, with $N - 1$ degrees of freedom (Pielou 1977), was determined for significant departure from randomness. A large chi-square value indicated that the null hypothesis of randomness was rejected in favor of the alternative hypothesis of aggregation.

$C(\alpha)$ Test Statistic. The $C(\alpha)$ test statistic, which uses a standard normal test, is similar to the chi-square test of D (Neyman 1959), but its alternative hypothesis is that aggregation is described by the beta-binomial. The standard normal test statistic (Z) is determined by:

$$Z = (n[N - 1]D - nN)/(2N[n^2 - n])^{1/2} \qquad (7)$$

This test may be more powerful than the chi-square test of D because the alternative hypothesis is specific, and the test is one-sided (Madden et al. 1995).

Binary Form of the Taylor Power Law. When data from all potato fields were collected, a binary form of Taylor power law was used to describe the relationship between the log of the observed variance (s^2) and the log of the binomial variance ($p[1 - p]/n$). The model was derived by Hughes and Madden (1992) and can be written as:

$$\log (s^2) = \log (a) + b \log(p[1 - p]) \qquad (8)$$

when n is constant and the data are represented as number of damaged stems. Simple linear regression using the procedure PROC GLM of SAS was used to estimate log (a) and b (SAS Institute 1990). In this formulation, $a = An^{-b}$. The interpretation of the slope (b) in this model is similar to the ordinary Taylor power law (Taylor 1961), where $b = 1$ indicates randomness and $b > 1$ signifies aggregation. A t-test, $t = (b - 1)/$ SEM b, with $N - 2$ degrees of freedom and a probability level of $\alpha = 0.05$, was used to evaluate the equality of b to 1 (Steel and Torrie 1980).

Sequential Sampling Plan Development. Sampling stop lines, operational characteristic and average sample number functions were calculated using the computer program BETABIN developed by J. Nyrop (Hoffmann et al. 1996). Stop lines were derived from the Wald sequential probability ratio test (Wald 1947) based on a binomial distribution because no test has been developed for the beta-binomial distribution. The parameters required for developing these stop lines were p_0 (proportion of damaged stems below which no treatment is required) and p_1 (proportion of damaged stems above which treatment is required), and α (type 1) and β (type 2) error rates. Operational characteristic and average sample number functions were determined for both the binomial and beta-binomial models using simulation. The operational characteristic function provided the probability of accepting the null hypothesis of no intervention or lower classification at any given level of *O. nubilalis* damage, (i.e., no recommendation for an insecticide application to prevent damage from exceeding the action threshold). The average sample number function represented the average number of samples needed to make the classification (i.e., damage is above or below the action threshold). The sequential sampling plan was designed such that 10 potato stems (sampling unit) would be sampled successively from a single row at each site within a field, and sites would be sampled until a control decision is made (equaling or exceeding a stop line), or until a maximum of 10 sites would be sampled per field (100 potato stems). If no decision could be made after 10 samples, a subjective decision would have to be made (e.g., sample at a later date, spray, or do not spray).

Operational characteristic and average sample number functions were generated for each of 2 action thresholds (i.e., 10 and 30% damaged stems) following the sampling procedure described above using both binomial and beta-binomial random variates as sample observations (Hoffmann et al. 1996). Beta-binomial random variates were determined using algorithms described by Press et al. (1986). Three values of θ (0.077, 0.151, and

0.307), which corresponded to the median, 75th and 99th percentile of the θs from the 41 fields sampled (see *Results*), were selected for the beta-binomial distribution simulations. The proportion of damaged stems above and below threshold, the probability of type 1 and type 2 errors, and the minimum number of sites to be sampled were varied, so that the most reasonable operational characteristic and average sample number functions could be determined. The maximum number of samples was fixed at 10 (i.e., 100 stems). One thousand iterations in a Monte Carlo simulation were used to generate all operational characteristic and average sample number functions, using the program of Hoffmann et al. (1996).

Comparison of Sequential Sampling Plan with Conventional Sampling Plan. The sequential sampling plan was compared with the conventional sampling plan used by commercial pest management scouts in the North Carolina potato crop by examining the extent to which the 2 plans resulted in disparate classification of the incidence of *O. nubilalis* damaged stems as above or below an action threshold of 10%. Scouts from a local agricultural consulting company used a sampling plan that called for sampling 10 stems per site at each of 10 sites within a field to collect data in each of 114 potato fields in eastern North Carolina during late April and May 1993 and 1995. The range in percentage of damaged stems in these fields was 0–35. On the basis of their experience, these scouts often classified damage levels as above or below threshold after sampling <10 sites within a field. The criteria for which sampling was stopped prematurely were subjective, but typically occurred when the level of *O. nubilalis* damage in the field was well above or below threshold.

Results and Discussion

Spatial Distribution Determination. *Probability Model Comparison.* The chi-square goodness-of-fit tests for the binomial and beta-binomial distributions could not be determined for data from individual potato fields because of the low N (=20). After pooling to legitimately test goodness-of-fit, calculated degrees of freedom were either zero or a negative value. Moreover, in several fields the total number of damaged stems per site was zero. All other statistical tests described previously were performed on data. In particular, the likelihood ratio test indicated that the beta-binomial provided a better fit of the data than the binomial in 70% of the fields with ≥6% *O. nubilalis* damaged stems (Table 1). When there were <6% damaged stems, the beta-binomial did not provide a better fit.

The maximum likelihood estimates of $\theta \pm$ SEM for each field are presented in Table 1. There was a weak linear relationship between values of θ and p ($F = 4.03$; df = 1, 31; $P = 0.053$; $y = 0.05 + 0.25x$; $R^2 = 0.22$) for the 32 fields with positive values of p. Although these results suggest that the performance of the sequential sampling plan would not be greatly affected by changes in θ, we took a conservative approach and evaluated the sequential plan under 3 different levels of aggregation (see *Materials and Methods*).

Variance-Ratio Test. Values of the index of dispersion (D) for data from each field were significantly different from 1 (i.e., aggregated) in 59% of the fields. Yet, 73% of the fields that had infestation levels ≥6% damaged stems had D values that were significantly >1 (Table 1). Those fields that had damage levels <6% typically had D values that were not different from 1 (82% of fields). Given these results, and those based on the likelihood ratio, fields with very low *O. nubilalis* damage (<6%) may be expected to have a random distribution ($D = 1$), whereas fields with damage ≥6% may be expected to generally have an aggregated distribution ($D > 1$).

C(α) Test Statistic. C(α) tests for data from individual fields indicated that the beta-binomial distribution described the data better than the binomial only when damage was ≥6%. Most (73%) individual fields that had ≥6% damaged stems had significant Z values ($P < 0.05$), whereas those fields that had <6% damaged stems had low and nonsignificant Z values (Table 1). Significant Z values ranged from 1.80 to 6.89 and were correlated well with fields that had significant D values.

Binary Form of the Taylor Power Law. There was a significant, linear relation between the log(observed variance) and the log(binomial variance) ($F = 572.49$; df = 1, 39; $P < 0.001$; $R^2 = 0.94$) (Fig. 1). Estimate of the intercept (log[a]) and the slope (b) ± SEM were 1.39 ± 0.06 and 1.15 ± 0.05, respectively (equation 8; Fig. 1). The slope was slightly greater than 1 ($t = 3.04$; df = 39; $P < 0.01$), indicating that the degree of aggregation varied with p. The generally increasing θ with increasing p is consistent with the power law results.

Sequential Sampling Plan Development. Decision lines for sequential sampling plans based on action thresholds of 10 and 30% damaged stems are shown in Fig. 2 A and B, respectively. A minimum of 3 and 2 sites must be sampled before a decision not to apply an insecticide to control *O. nubilalis* can be made when the action thresholds are 10 and 30% (0.1 and 0.3 proportion damaged stems), respectively. If all 10 sites are sampled and the cumulative number of infested stems is between either 6 and 12 (10% threshold) or 26 and 33 (30% threshold) (i.e., decision within the continue sampling category), the user would have to make a subjective decision of whether to implement control measures or to sample the field again at a later date.

The sequential sampling plan based on a threshold of 10% damaged stems (0.1 proportion damaged) had the following parameters: $p_0 = 0.05$, $p_1 = 0.15$, α (type 1) = β (type 2) = 0.05. (Note, α

Table 1. Description of the distribution (binomial or beta-binomial) of *O. nubilalis* damaged potato stems from fields in eastern North Carolina in 1991, 1992, 1993, and 1994

Field name	Date sampled	Mean infested stems, %[a]	Likelihood ratio[b]	Estimated $\theta \pm$ SEM[c]	D^d	Z values for $C(\alpha)$ test[e]
Salem Church I	9 June 1994	0.5	0.00NS	0	1.01NS	−0.151NS
Lamb	28 May 1993	0.5	0.00NS	0	1.01NS	−0.151NS
Mary Daniels	5 June 1992	1.5	0.00NS	0	0.91NS	−0.457NS
Magnolia	13 May 1992	1.5	2.00NS	0.101 ± 0.143	1.62*	1.799*
Swamp Rd. I	9 June 1994	2.0	0.00NS	0	0.86NS	−0.612NS
Turtle	14 May 1992	2.0	0.96NS	0.052 ± 0.080	1.40NS	1.088NS
Near N-slope	20 May 1992	2.0	0.96NS	0.052 ± 0.080	1.40NS	1.088NS
Tanglewood I	9 June 1994	3.5	0.00NS	0	1.02NS	−0.101NS
Brooks I	15 May 1991	3.5	1.85NS	0.062 ± 0.080	1.64*	1.873*
N-Slope/N-B-C	27 May 1993	4.5	0.00NS	0	0.85NS	−0.638NS
Paul I	22 May 1991	5.5	1.78NS	0.065 ± 0.070	1.51NS	1.461NS
Tony B. I	31 May 1993	6.0	5.45*	0.121 ± 0.103	2.13*	3.404*
Paul II	22 May 1991	6.0	2.46NS	0.084 ± 0.077	1.57NS	1.631NS
Paul III	22 May 1991	6.5	5.03*	0.128 ± 0.099	1.95*	2.851*
Salem Church	31 May 1993	7.5	14.82*	0.307 ± 0.196	2.86*	5.736*
Tanglewood II	9 June 1994	8.0	0.37*	0.025 ± 0.045	1.23NS	0.562NS
Trap	31 May 1993	8.5	3.30NS	0.095 ± 0.077	1.66*	1.928*
Desert I	10 June 1994	9.5	6.07*	0.158	2.38*	4.217*
Turtle	25 May 1993	10.5	9.08*	0.014 ± 0.089	2.74*	5.348*
N-B Canal	25 May 1993	11.5	2.95*	0.077 ± 0.062	1.68*	1.997*
Salem Church II	9 June 1994	12.0	1.60NS	0.058 ± 0.060	1.46NS	1.275NS
Taylor	21 May 1991	13.0	14.08*	0.245 ± 0.137	2.62*	4.948*
Phorate	15 May 1991	13.5	0.69NS	0.038 ± 0.054	1.29NS	0.741NS
Hot Spot	8 June 1992	16.0	7.24*	0.117 ± 0.072	2.30*	3.958*
Silo	25 May 1993	18.0	0.00NS	0	0.97NS	−0.262NS
Harris	8 May 1991	19.0	5.98*	0.129 ± 0.081	1.91*	2.710*
Combine	18 May 1993	19.5	0.40NS	0.026 ± 0.044	1.24NS	0.590NS
Hot Spot	18 May 1993	19.5	0.50NS	0.025 ± 0.043	1.31NS	0.802NS
Tony B. II	31 May 1993	21.0	21.07*	0.282 ± 0.132	3.23*	6.894*
Near Turtle	9 June 1992	24.0	9.11*	0.151 ± 0.084	2.27*	3.867*
Bobcat	25 May 1993	24.0	0.00NS	0.001 ± 0.035	1.06NS	0.029NS
Desert II	10 June 1994	24.5	2.43*	0.064 ± 0.056	1.62*	1.798*
Swamp Rd. II	9 June 1994	24.5	8.01*	0.154 ± 0.088	2.08*	3.240*
Railroad Bed	4 June 1993	25.5	10.08*	0.192 ± 0.109	2.19*	3.59*
Near Hot Spot I	18 May 1993	30.0	8.20*	0.126 ± 0.069	2.31*	3.968*
Swamp	28 May 1993	32.0	3.63NS	0.079 ± 0.061	1.77*	2.273*
N-Slope/RR	25 May 1993	36.5	17.71*	0.248 ± 0.115	2.78*	5.479*
Transformer	31 May 1993	38.5	6.13*	0.111 ± 0.070	2.01*	3.041*
Tyson	8 May 1991	53.0	15.91*	0.209 ± 0.103	2.75*	5.378*
James I	4 June 1993	61.5	12.67*	0.178 ± 0.089	2.55*	4.730*
James II	4 June 1993	73.5	19.36*	0.258 ± 0.120	3.10*	6.469*

[a] Mean *O. nubilalis* damaged potato stems assessed from 20 sites per field (N = 20) using a 10-stem sampling unit (n = 10) (total = 200 stems per field).

[b] Likelihood ratio test statistic for evaluating the difference in likelihood function values for the binomial and beta-binomial distributions. An asterisk signifies that the beta-binomial fits the data better than the binomial distribution ($\chi^2_{df=1;\ P=0.05} \geq 3.84$), and NS indicates that the beta-binomial and binomial have equal fits to the data ($\chi^2_{df=1;\ P=0.05} < 3.84$).

[c] θ, The index of aggregation ± SEM. Absence of SEM indicates that the maximum likelihood estimation (MLE) was not obtained.

[d] Index of dispersion (D). An asterisk indicates that the distribution of damaged potato stems was overdispersed, and an NS indicates randomness, using a chi-square test (χ^2) (df = 19, $P \leq 0.05$).

[e] Standard normal test statistic. An asterisk indicates that the distribution of damaged potato stems was overdispersed (i.e., specifically by the beta-binomial), and an NS indicates randomness ($P \leq 0.05$).

and β here are different from the parameters of the beta-binomial [equations 2 and 3].) Values of type 1 and 2 errors corresponded with the probability that a control decision would be made when control was not needed, and the probability that a control decision would not be made when control was needed, respectively.

The steepest operational characteristic function and the greatest maximum average sample number function corresponded with the binomial model that had no minimum or maximum number of samples (i.e., nominal case) (Fig. 3 A and B). All other operational characteristic and average sample number functions were determined based on a minimum of 10 stems per site (n = 10) and a maximum of 100 stems (N = 10 sites) required to be sampled. Of these curves, the binomial model had the steepest operational characteristic function and greatest average sample number function, followed by the beta-binomial models with increasing values of θ (Fig. 3 A and B). Thus, for fields with a beta-binomial distribution of *O. nubilalis* damage, the probability of making type 1 and 2 errors increased as θ increased. For example, if the proportion of damaged stems was above threshold (e.g., 0.15) and θ was high (0.307), nearly 3 out of

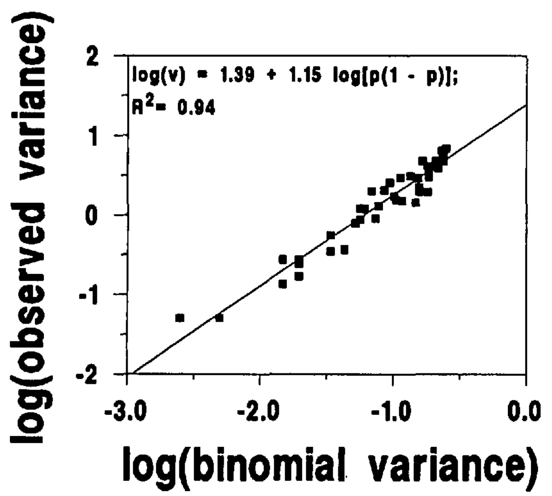

Fig. 1. Relationship between the log of the observed variance (s^2) and the log of the binomial variance ($p[1-p]$) using a binary form of the Taylor power law. Each data point represents one of the 41 fields sampled during 1991–1994.

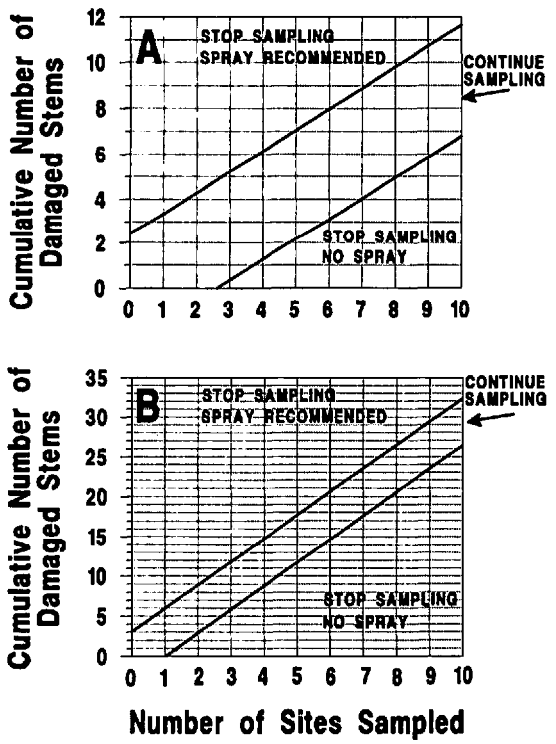

Fig. 2. (A) Sequential sampling plans for *O. nubilalis* control in potato using a 10-stem sampling unit (1 site = 10 stems) and a threshold of 10% damaged stems (0.1 proportion damaged), and (B) using a threshold of 30% damaged stems (0.3 proportion damaged). Sequential sampling stop lines were based on the Wald sequential probability ratio test (1947) formulae. Probabilities of type 1 (α) and type 2 (β) errors were each 5%.

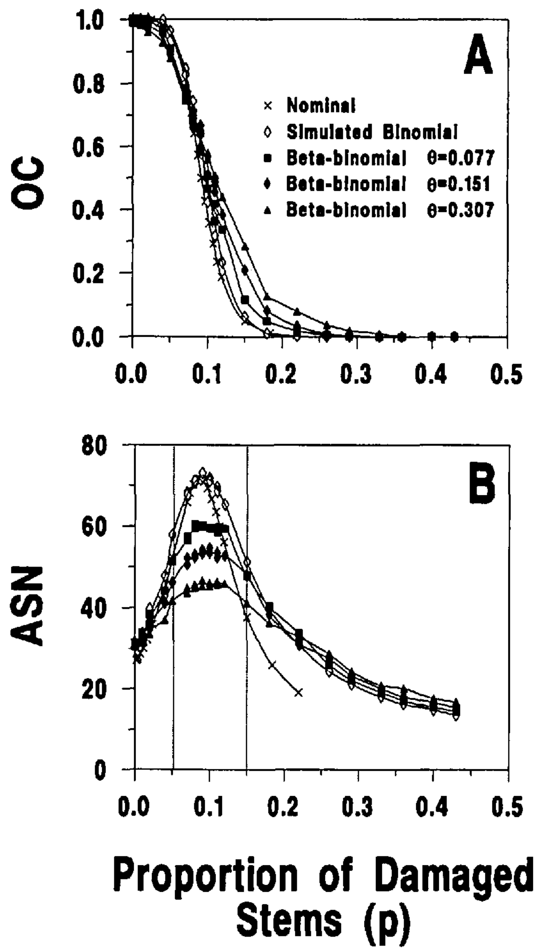

Fig. 3. (A) Operational characteristic and (B) average sample number functions for a threshold of 10% damaged stems (0.1 proportion damaged) with the following parameters: $p_0 = 0.05$, $p_1 = 0.15$, and $\alpha = \beta = 0.05$. Nominal lines refer to binomially distributed samples with no minimum or maximum sample size. Simulated binomial and beta-binomial lines were constructed based on a minimum sample size of 10 stems and a maximum of 100 stems. Area under the operational characteristic lines refers to damage levels in which the probability of no recommendation for an insecticide application will be made. Values of θ refer to levels of damage aggregation and correspond with the median, 75th and 99th percentile of θs from 41 individual potato fields.

10 times a recommendation for an insecticide application would not be made.

Hoffmann et al. (1996) had similar results when developing a sequential sampling plan for use in scheduling control of Lepidopteran pests in sweet corn in New York. They concluded that the relatively high operational characteristic values at threshold were acceptable because the sampling plan would likely be used more than once for monitoring pest damage in the same field, especially if damage was below threshold, and would result in a decrease in the overall operational characteristic

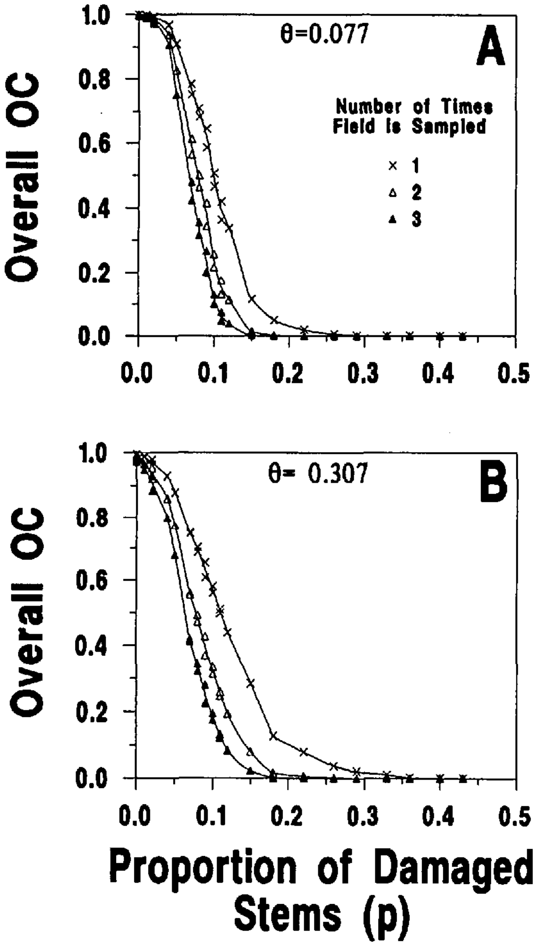

Fig. 4. Overall operational characteristic (OC) functions when the sequential sampling plan based around a threshold of 10% damaged stems are used to make a control decision for a constant damage level after a field is sampled 1, 2, or 3 times. Values of θ refer to levels of aggregation that correspond with the median (0.077) (A) and 99th percentile (0.307) (B) of θs from 41 individual potato fields.

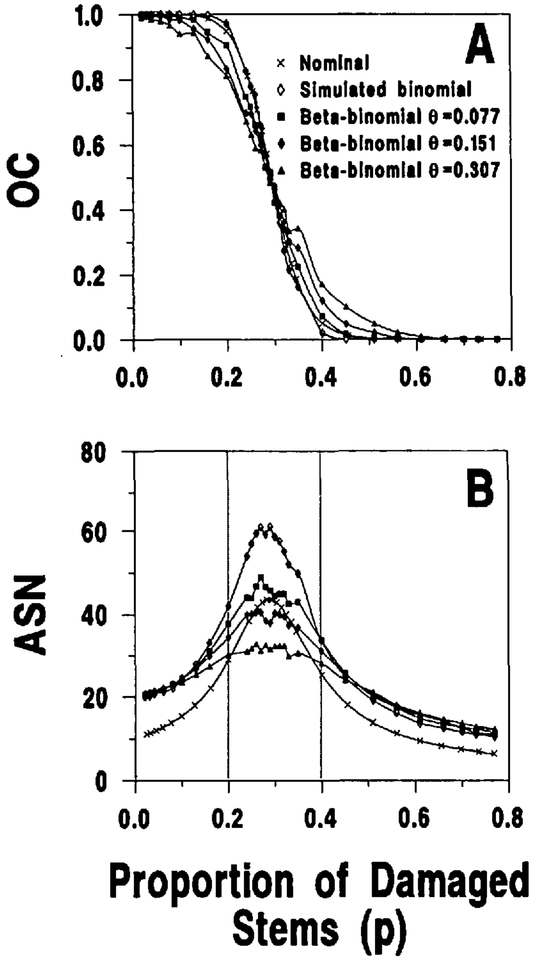

Fig. 5. (A) Operational characteristic (OC) and (B) average sample number (ASN) functions for a threshold of 30% damaged stems (0.3 proportion damaged) with the following parameters: p_0 = 0.2, p_1 = 0.4, and $\alpha = \beta$ = 0.05. Nominal, simulated binomial and beta-binomial lines were constructed using the same sample size restrictions referred to previously. Values of θ refer to levels of damage aggregation and correspond with the median, 75th and 99th percentile of θs from 41 individual potato fields.

function after each sampling bout. The overall operational characteristic function for the entire period an individual field is sampled would be the probability that a decision not to spray would result for any of the times the field is sampled. Thus, if the density or damage level is constant, the overall operational characteristic (OC) would be OC^s where s is the number of sampling bouts (Nyrop et al. 1994). Results with our data (shown in Fig. 4 A and B) illustrate a decrease and a shift of the operational characteristic function to the left on the proportion of damaged stems axis after each sampling bout. Given a θ = 0.307 and a proportion of damaged stems >0.15, there would be ≥95% probability of making a recommendation for an insecticide application after sampling the field a 2nd time.

The sequential sampling plan based around an action threshold of 30% damaged stems (0.3 proportion damaged) had the following parameters: p_0 = 0.2, p_1 = 0.4, $\alpha = \beta$ = 0.05. The steepness of the operational characteristic functions and the height of the maximum average sample number functions were similar to those of the sequential sampling plan based around the 10% threshold (Fig. 5 A and B). At a proportion of damaged stems of 0.3 , the operational characteristic functions were relatively high for all θs. Yet, operational characteristic values decreased and shifted to the left on the proportion of damaged stems axis after each sampling bout and were considered accept-

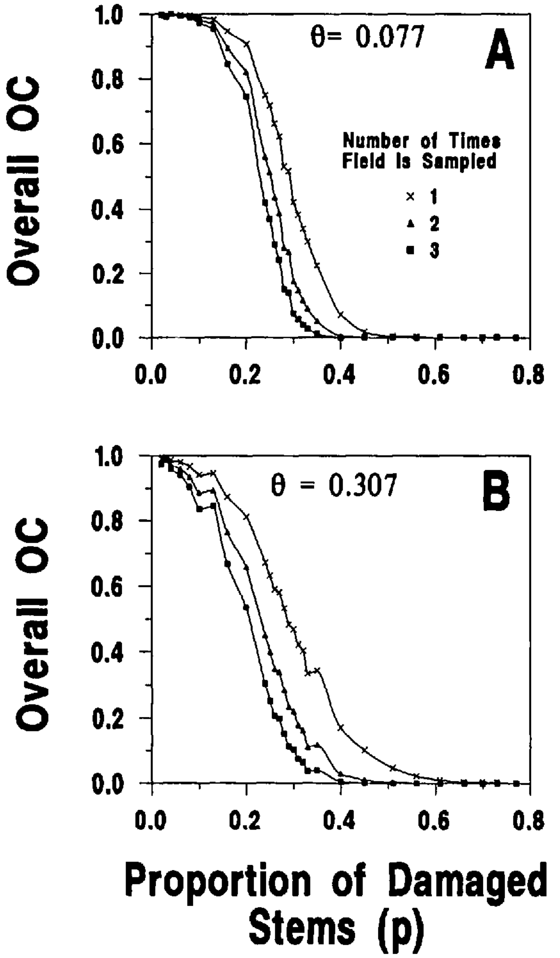

Fig. 6. Overall operational characteristic (OC) functions when the sequential sampling plan based around a threshold of 30% damaged stems are used to make a control decision for a constant damage level after a field is sampled 1, 2, or 3 times. Values of θ refer to levels of aggregation that correspond with the median (0.077) (A) and 99th percentile (0.307) (B) of θs from 41 individual potato fields.

able when the damage exceeded 0.35 (Fig. 6 A and B).

Comparison of Sequential Sampling Plan with Conventional Sampling Plan. Although simulated operational characteristic and average sample number functions provided a thorough estimation of the precision and practicality of the sequential sampling plan, these functions were based on parameters derived from our samples of 41 fields, which were assumed to be appropriate for all fields. In particular, the degree of aggregation of *O. nubilalis* damage in each commercial field (i.e., θ) calculated using the BBD may not have provided a reliable estimate of the aggregation in these fields. Therefore, we believed that it was important to compare control decisions made by the sequential sampling plan with those made by the conventional plan using data collected from the field.

Classifications of damage based on the sequential sampling plan agreed closely with those by the conventional sampling plan. There was only 1 instance (0.9% of fields) in which the sequential plan classified a field as above threshold when the conventional plan classified it as below threshold (i.e., type 1 error). There were only 2 instances (1.8% of fields) in which the sequential plan classified fields as below threshold when the conventional plan classified them as above threshold (i.e., type 2 error). Protection against the more serious type 2 error occurs by sampling fields repeatedly (see above discussion). There were 9 occasions (8% of fields) when no definitive decision was made for a control measure after the 10th site had been sampled (i.e., the cumulative number of damaged stems was between the lower and upper sampling stop lines). In this situation, the sequential sampling plan performed no differently than the conventional plan.

Performance of the sequential sampling plan was superior to the conventional sampling plan. The sequential sampling plan reduced the overall average number of sites required to make a control decision by 57% (fixed ± SD: 8.7 ± 2.1 and sequential ± SD: 3.7 ± 1.8). When the percentage of damaged stems was 0–9%, the scouts using the conventional plan averaged (±SD) 9.1 ± 1.8 sites before a control decision was made, whereas the sequential plan required sampling an average of 4.2 ± 1.6 sites (54% reduction) before a decision could be made. Similarly, when the percentage of damaged stems was ≥10%, scouts using the conventional plan averaged (±SD) 7.9 ± 2.5 sites before a control decision was made, whereas the sequential plan required sampling an average of 2.8 ± 1.7 sites (65% reduction). These results are consistent with other sequential sampling plans that reduce the number of samples needed to make a control decision by an average of 40–60% compared with fixed sampling (Fowler and Lynch 1987).

Adoption of the sequential sampling plan for use in timing insecticide applications for *O. nubilalis* control in potato should improve *O. nubilalis* management in potato. This sampling plan is easy to use, reduces the average number of samples required to make the decision, and provides known probabilities of making type 1 and 2 errors.

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References Cited

Averre, C. W., and K. A. Sorensen. 1979. Potato pest alert. North Carolina Agricultural Extension Service, Raleigh, NC.

Fisher, R. A. 1970. Statistical methods for research workers, 14th ed. Hafner, New York.

Fowler, G. W., and A. M. Lynch. 1987. Bibliography of sequential sampling plans in insect pest management based on Wald's sequential probability ratio test. Gt. Lakes Entomol. 20: 165–171.

Gates, C. E., and F. G. Ethridge. 1970. A generalized set of discrete frequency distributions with FORTRAN program. Int. Assoc. Math. Geo. 4: 1–24.

Hoffmann, M. P., J. P. Nyrop, J. J. Kirkwyland, D. M. Riggs, D. O. Gilrein, and D. D. Moyer. 1996. Sequential sampling plan for scheduling control of Lepidopteran pests of fresh market sweet corn. J. Econ. Entomol. 89: 386–395.

Hughes, G., and L. V. Madden. 1992. Aggregation and incidence of disease. Plant Pathol. 41: 657–660.

1993. Using the beta-binomial distribution to describe aggregated patterns of disease incidence. Phytopathology 83: 759–763.

Johnson, N. L., S. Kotz, and A. W. Kemp. 1992. Univariate discrete distributions, 2nd ed. Wiley, New York.

Kennedy, G. G., and T. E. Anderson. 1981. Considerations for management of the European corn borer on potatoes, pp. 204–222. *In* J. Lashomb and R. Casagrande [eds.], Potato pest management. Dowden, Hutchinson, and Ross, Stroudsburg, PA.

Madden, L. V., and G. Hughes. 1994. BBD-computer software for fitting the beta-binomial distribution to disease incidence data, version 1.2. Plant Dis. 78: 536–540.

1995. Plant disease incidence: distributions, heterogeneity, and temporal analysis. Annu. Rev. Phytopathol. 33: 529–564.

Madden, L. V., G. Hughes, and M. A. Ellis. 1995. Spatial heterogeneity of the incidence of grape downy mildew. Phytopathology 85: 269–275.

Nault, B. A., and G. G. Kennedy. 1996. Timing insecticide applications for managing European corn borer (Lepidoptera: Pyralidae) infestations in potato. Crop Prot. 15: 465–471.

Nault, B. A., and K. A. Sorensen. 1996. Life history and management of European corn borer in potatoes. North Carolina Cooperative Extension Service Report 2. North Carolina State University, Raleigh, NC.

Neyman, J. 1959. Optimal asymptotic tests of composite hypotheses, pp. 213–234. *In* U. Granander [ed.], Probability and statistics. The Harold Crainer volume. Wiley, New York.

Nyrop, J. P., M. R. Binns, W. van der Werf, and J. Kovach. 1994. Cascading tripartite binomial classification plans to monitor European red mite (Acari: Tetranychidae) through a season: development and evaluation of a new methodology for pest monitoring. Exp. Appl. Acarol. 18: 123–153.

Pielou, E. C. 1977. Mathematical ecology. Wiley, New York.

Press, W. H., B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling. 1986. Numerical recipes. Cambridge University Press, Cambridge.

SAS Institute. 1990. SAS/STAT user's guide version 6. SAS Institute, Cary, NC.

Skellam, J. G. 1948. A probability distribution derived from the binomial distribution by regarding the probability of success as variable between sets of trials. J. R. Stat. Soc. B. 10: 257–261.

Steel, R. G. D., and J. H. Torrie. 1980. Principles and procedures of statistics: a biometrical approach. McGraw-Hill, New York.

Taylor, L. R. 1961. Aggregation, variance and the mean. Nature (Lond.). 189: 732–735.

Toth, Jr., S. J. 1995. Survey of pesticide use by North Carolina potato growers in 1994. North Carolina State University, Raleigh, NC.

Wald, A. 1947. Sequential analysis. Wiley, New York.

Williams, D. A. 1975. The analysis of binary responses from toxicological experiments involving reproduction and teratogenicity. Biometrics 31: 949–952.

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