Sequential Sampling for Panicle Caterpillars (Lepidoptera: Noctuidae) in Sorghum

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ABSTRACT Panicle caterpillars comprise an economically important insect pest complex of sorghum throughout the Great Plains of the United States, particularly in Kansas, Oklahoma, and Texas. The sorghum panicle caterpillar complex consists of larvae of two polyphagous lepidopteran species: the corn earworm, *Helicoverpa zea* (Boddie), and fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae). Sampling for panicle caterpillars in sorghum fields is usually accomplished by the beat bucket sampling technique with a fixed sample size of 30 beat bucket samples of one sorghum panicle each per 16.2 ha of field. We used Wald's sequential probability ratio test for a negative binomial distribution to develop a sequential sampling plan for panicle caterpillars. In total, 115 sorghum fields were sampled in Kansas, Oklahoma, and Texas from June to August 2010. Panicle caterpillars had an aggregated distribution of counts confirmed by Pearson's chi-square statistic for lack of fit to the negative binomial distribution for each sampled field. A sequential sampling plan was developed using a high threshold (an economic threshold) of 0.5 caterpillars per sorghum panicle, a low threshold (a safe level) of 0.20 caterpillars per panicle, and fixed error rates ($\alpha = 0.10$ and $\beta = 0.05$). At caterpillar densities >0.45 and <0.12 per panicle, the average number of panicles inspected to make a decision was less than the current recommendation of 30. In a 2013 validation test of 25 fields, the expected number of samples taken from average sample number curve was in close agreement with the number of samples required using the sequential plan ($r^2 = 0.93$), and all fields were correctly classified when compared with a fixed sample size result. The plan improved upon current sampling recommendations for panicle caterpillars in sorghum because at known acceptable fixed error rates fewer samples were required when caterpillars are scarce or abundant, whereas more samples were required to make decisions with the same acceptable error rates when densities were near the economic thresholds.

KEY WORDS integrated pest management (IPM), sequential sampling, corn earworm, fall armyworm, *Helicoverpa zea*

The United States produces the most sorghum of any nation, and most of that is produced in Kansas, Nebraska, Oklahoma, and Texas (U.S. Department of Agriculture [USDA] 2010). Panicle caterpillars comprise an economically important insect pest complex of sorghum throughout the Great Plains of the United States, particularly in Kansas, Oklahoma, and Texas. The sorghum panicle caterpillar complex consists of two polyphagous lepidopteran species: the corn earworm, *Helicoverpa zea* (Boddie), and the fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae). In a recent survey, growers ranked the panicle worm complex as the second most important insect pest behind greenbugs (Pendleton et al. 2000). Moths of these species lay eggs on the leaves and panicles of sorghum during the summer, and feeding by the larvae can cause severe economic damage to the sorghum crop. Burkhardt (1957) observed that one to two *H. zea* larvae per sorghum panicle resulted in 10–25% grain loss. Nearly all of the damage observed in the field is caused by third- to sixth-instar *H. zea* feeding on sorghum seeds in the soft dough stage (Kinzer and Henderson 1968). Kinzer and Henderson (1968) also found that first and second *H. zea* instars preferred flowering sorghum. More recently, Soper et al. (2013) demonstrated that *H. zea* and *S. frugiperda* (corn strain) larvae feeding on sorghum seeds grow at equivalent rates and the soft dough stage of sorghum was most vulnerable to yield loss by these species.

The beat bucket technique is considered the most efficient way to sample for panicle caterpillars and

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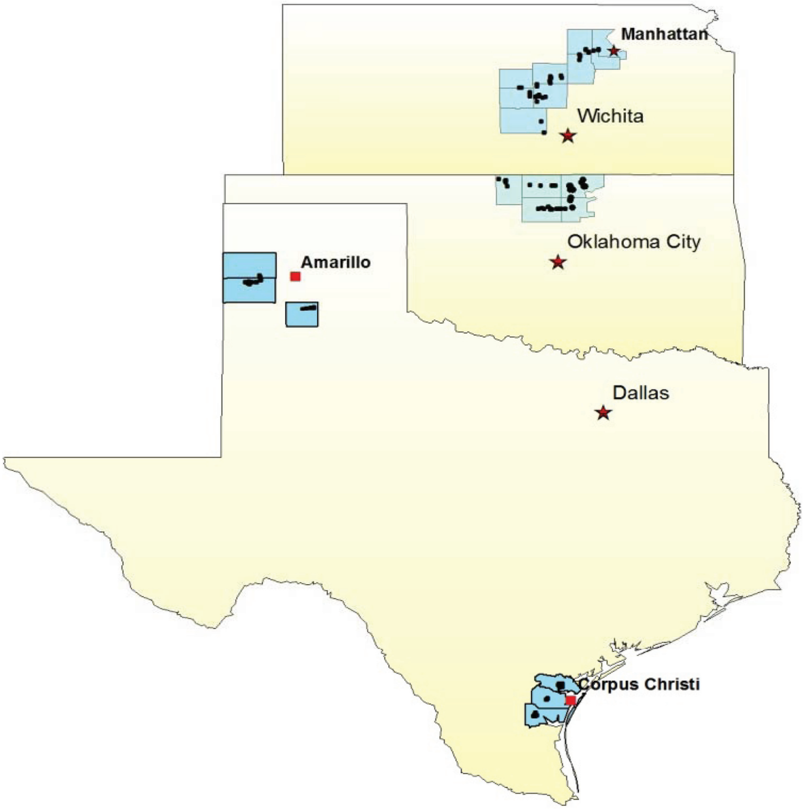

Fig. 1. Locations of four sorghum-growing areas where panicle caterpillars were sampled in sorghum fields. (Online figure in color.)

some other panicle-feeding insects in sorghum (Teetes and Wiseman 1979, Merchant and Teetes 1992). A major limitation of sampling by beat buckets is that it is based on a fixed sample size, which was set at 30 beat bucket samples per 16.2 ha of field by Cronholm et al. (2007). Sampling with a fixed sample size is often inefficient because too much time is spent sampling fields with low or high population densities (Binns 1994). A second limitation of a fixed sample size is that decisions on whether the economic threshold has been exceeded have variable and unknown error rates. Thus, a grower makes a decision on whether the population may economically damage the crop with a generally unknown level of confidence as to whether the correct decision is being made. Sequential sampling can overcome the limitations for fixed sample size techniques and can sometimes result in 50% or greater reduction in the time required to sample a field (Binns 1994), which may make routine sampling more feasible for growers. Our objective was to develop a sequential sampling plan for use in integrated pest management (IPM) decision-making for panicle caterpillars in sorghum. The sampling data from 115 production fields located in Kansas, Oklahoma, and Texas were used to develop a sequential sampling procedure for sorghum panicle caterpillars. The procedure was validated with independent data from another 25 fields.

Materials and Methods

Sampling Panicle Caterpillars. Sorghum fields in four geographical areas in Kansas, Oklahoma, and Texas where sorghum is intensively grown were sampled during June–August 2010 (Fig. 1). Within each area, ≥15 sorghum fields were selected for sampling. Each field was sampled one time using the beat bucket sampling technique (Teetes and Wiseman 1979). An individual sample was taken by vigorously shaking one sorghum panicle inside a white 5-gallon bucket and by counting the number of dislodged panicle caterpillars in the bucket. Twenty-four beat bucket samples were taken from each of two adjacent 8.1-ha sections in each field, for a total of 48 beat bucket samples per field according to the uniform sampling pattern illustrated in Fig. 2. The sampling pattern sometimes had to be modified to adjust to differences in the shape and size of fields, but we always strived for uniform coverage of each 8.1-ha block. Sorghum panicles were not sampled within a ≈10-m border from the edge of the field. The two 8.1-ha sections were contiguous to form a 16.2-ha block. In selected fields, this procedure was repeated in two 16.2-ha blocks within the field, so 96 beat bucket samples were taken over a total area of 32.4 ha. Sampling was done during the flowering through the hard dough stages. All panicle caterpillars

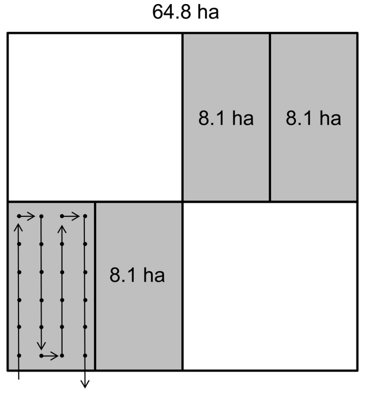

Fig. 2. General layout of sampling plots in sorghum fields and the pattern used to sample plots for panicle caterpillars.

in each beat bucket sample were counted and recorded as small (<6 mm in length), medium (6–13 mm in length), or large (>13 mm in length). Data for medium and large caterpillars were used to develop the sequential sampling plan (see next section).

The sampling design described above was constructed to evaluate whether the 16.2-ha management unit currently recommended in sampling guidelines (Cronholm et al. 2007, Royer 2008) is appropriate or whether a smaller, 8.1-ha unit, is more appropriate. The design secondarily provided information on whether sampling one 16.2-ha unit per field provided an appropriate representation of panicle caterpillar infestation for the entire field, or whether more than one such unit would need to be sampled to make an appropriate management decision across sections of large fields. We statistically compared median numbers of panicle caterpillars per panicle among adjacent 8.1-ha units of a field using Wilcoxon signed rank tests. If differences were nonsignificant, we inferred that a 8.1-ha sampling area was sufficient to make a treatment decision for a field as large as 16.2 ha. Conversely, rejection of the null hypothesis (i.e., equal medians) infers that the entire 16.2-ha sampling area was more appropriate.

Likewise, we used Wilcoxon signed rank tests to compare median numbers of caterpillars per panicle among the two 16.2-ha units within the same field (not necessarily adjacent). If differences were nonsignificant, the inference was that sampling within one 16.2-ha block would suffice to make a treatment decision for a field at least 32.4 ha in area.

Developing a Sequential Sampling Plan. Insects often have aggregated spatial distributions, which can vary among environments, with changes in population density, sampling method, and other factors (Southwood 1978). We used Taylor's power law (Taylor 1961) to assess whether the spatial distribution of panicle caterpillars differed among the four geographic regions where sampling was conducted. Variation in spatial distribution would manifest in differences in parameters of Taylor's power law among geographic regions. To test for differences in the parameters we fit a linear regression model.

$$log(s^2) = log(a) + b \cdot log(\bar{X})$$

where log(a) and b were estimated for each of the four regions using a homogeneity of slopes regression model (Neter and Wasserman 1974, pages 304–312). Significant variation in the model parameters, particularly in b, among regions would indicate that characteristics of the environment or other factors influencing panicle worm spatial distribution in sorghum fields varied enough among regions that sampling effectiveness and error rates associated with population estimation might be affected (Southwood 1978). In this event, it would be advisable to develop sampling plans independently for each region. This analysis showed minimal variation in parameters among regions (see results), indicating that a single sampling plan could be developed for use in the four regions.

Numbers of panicle caterpillars per panicle were analyzed to evaluate whether caterpillars were aggregated among sorghum panicles in a field. The statistic $(n - 1)\ s^2/\bar{X}$ has a chi-square distribution with $n - 1$ degrees of freedom, and is commonly used as a test for a random distribution of counts (Elliott 1977). If the test statistic is significantly greater than one, an aggregated distribution of counts is supported. Because $(n - 1)\ s^2/\bar{X}$ is distributed as a chi square, the sum of such statistics from n_1 fields sampled independently is also distributed as a chi square with $n_1(n - 1)$ degrees of freedom. Therefore, for our application, the chi square distributed statistic $\Sigma_1^{n1}\ (n_i-1)s_i^2/\bar{X}_i^2$ was used as a test for randomness of panicle caterpillar counts among the $n_1 = 103$ sorghum fields where panicle caterpillars were detected.

Once the hypothesis of a random distribution of count data were rejected (see results), we selected the negative binomial probability distribution as a prospective model for describing numbers of panicle caterpillars per sorghum panicle. The negative binomial distribution has proven to be useful for describing count data from samples of insects (Southwood 1978). Pearson's chi-square test (Pearson 1900) was used to test for goodness of fit to the negative binomial distribution of the counts for each sample. Pearson's chi-square statistic was calculated for each sampled field and tested for significant lack of fit at $\alpha = 0.05$. The parameter k of the negative binomial distribution was estimated by the method of moments for each sample and used in calculating the chi-square test. The method of moments provides efficient estimates of k, when both k and the mean of counts are less than four (Anscombe 1950). This was usually the case for our data; therefore, the number of significant chi-square tests, indicating lack of fit, out of the total number of tests was used to determine whether the negative binomial distribution adequately described the distribution of the number of caterpillars per panicle.

The sequential probability ratio test (SPRT; Wald 1947) was used to develop a sequential sampling procedure once a distribution model was selected. As a candidate model, we selected SPRT for the negative binomial distribution (see results). To use SPRT, the parameter k of the negative binomial must be constant over the range of panicle caterpillar population densities that exceed the economic threshold. An estimate of a common k, designated as k_c, was calculated using the method proposed by Bliss and Owens (1958). This method involves calculating the sample size, mean, and variance for each sample and calculating a linear regression through the origin to obtain an initial estimate of k_c. The inverse of the slope of the regression line is an estimate of k_c. In the regression, y_i (estimated as $S_i^2 - X$) was regressed against x_i (estimated as $X_i^2 - [S_i^2/n_i]$). The estimate of k_c from the unweighted regression was used to calculate weights for a subsequent weighted regression. The weights for each sample were inversely proportional to the sample variance (Bliss and Owens 1958) with parameters k_c and μ. The estimate of k_c from the weighted regression was compared with the previous estimate. When k_c changed minimally among successive iterations, the process was discontinued.

We tested for the suitability of a common k for all sampled fields (Bliss and Owens 1958). The test required calculating the sample size, mean, and variance for each sample and calculating linear regressions of y_i on x_i (see above) first through the origin and then with a y-intercept. F-tests were constructed based on appropriate sums of squares from the two regressions to test the null hypothesis of a common k versus the alternative hypothesis that k differed for at least one sample (see Young and Young 1998, pages 114–117 for complete details).

The SPRT for the negative binomial distribution tests the following hypotheses:

$$H_o: \mu = \mu_o$$

$$H_1: \mu = \mu_1$$

where μ_1 ($>\mu_o$) is the number of caterpillars per panicle above which insecticidal treatment is advised (economic threshold), and μ_o is the corresponding number where the infestation is considered below the economic threshold (safe level). We constructed a sequential sampling plan based on SPRT for an economic threshold of 0.5 caterpillars per panicle. We chose a safe level (i.e., no-treat decision) of 0.20 caterpillar per panicle which was set at less than half the economic threshold, and chose $\alpha = 0.10$ and $\beta = 0.05$. We set $\beta < \alpha$ (i.e., $\alpha = 0.10$ and $\beta = 0.05$) because decreasing an error rate increases the number of panicles required to make a decision, and an erroneous decision to treat a field that was slightly below the safe threshold (α) was considered less serious than failing to treat a field that was above the economic threshold (β).

Sequential sampling stop lines, operating characteristic (OC) curves, and average sample number (ASN) curves were developed using standard methodology and formulae (see Young and Young 1998, pages 157–170). For our application, the ASN specifies the average number of samples required to make a decision as a function of the mean number of caterpillars per sorghum panicle, whereas the OC gives the probability of accepting the null hypothesis (H_o) also as a function of the mean.

Validating the Candidate SPRT. To validate the sequential sampling plan, 25 sorghum fields were sampled from the Texas Coastal Plains ($n = 5$) and central Oklahoma ($n = 20$) during July 2013. In total, 48 panicles were sampled sequentially within an 8.1-ha section of the field by the procedure described previously. The mean of the 48 samples was used to estimate the true population mean. The number of medium plus large caterpillars per panicle was recorded for each panicle sampled from a field until a treat or no-treat decision was made. Then sampling was continued until the 48 panicles were inspected. The decision derived from the sequential sampling plan was compared with the mean number of caterpillars calculated from counts for the 48 panicles. The decision from sequential sampling was considered correct if the mean from the 48 panicles agreed with the stop sampling decision ($\geq$0.50 for a treat decision or $\leq$0.20 for a no-treat decision) and was considered incorrect otherwise. In the case where the sample mean was between 0.20 and 0.50 caterpillars per panicle, a treat decision or a no-treat decision was technically incorrect. However, an inherent feature of sequential sampling is that a decision will eventually be made even when the population mean falls between the upper and lower stop lines, and the infestation will be classified as either above the upper limit or below the lower limit. Therefore, for validation we considered the decision to be correct if a no-treat decision was achieved when the mean was $\leq$0.35, and if a treat decision was achieved when the mean was $\geq$0.35, where 0.35 is the midpoint between 0.20 and 0.50.

All statistical tests, except those for chi-square goodness of fit to the negative binomial distribution, were accomplished using procedures in SAS 9.1 (SAS Institute 2004, Cary, NC). A program was written in Pro Fortran11.1 (Absoft Corp., Troy, MI) to calculate chi-square goodness of fit tests to the negative binomial distribution.

Results and Discussion

Panicle Worm Sampling. Thirty-seven fields were sampled in central Kansas, 40 in north central Oklahoma, 23 in the Texas High Plains, and 15 in the Texas coastal region, for a total of 115 fields. Sampling data from 12 fields were not used because no panicle caterpillars were found or because in a few cases collection errors made the data for a field unusable. Thus, panicle caterpillar count data from a total of 103 fields were used in analyses. The number of caterpillars per sorghum panicle for the 103 fields ranged from 0.02 to 3.17, with a mean of 0.42 (SE = 0.049) caterpillars per panicle.

Five out of 103 Wilcoxon tests comparing the number of caterpillars per panicle among adjacent 8.1-ha blocks within fields were significant. The difference in density between 8.1 ha ranged from 0 to 1.54 caterpillars per panicle with a mean across all fields of 0.05 caterpillars per panicle (SE = 0.03). For 16.2-ha blocks the difference in density ranged from 0 to 0.41 caterpillars per panicle with a mean across all fields of 0.03 caterpillars per panicle (SE = 0.07). For 8.1-ha blocks, the number of significant Wilcoxon tests was close to the number that would be expected by chance with $\alpha = 0.05$. This result supported the conclusion that a

Table 1. Estimates of Taylor's power law parameters and *t*-statistics testing the hypothesis that the parameter equals zero derived from a homogeneity of slopes regression model for panicle caterpillars per panicle in sorghum fields from four geographic regions in Kansas, Oklahoma, and Texas

Geographic region	Parameter (*SE*)					
	log(a)	*t*	*P*	b	*t*	*P*
Texas Coastal Plains	0.64 (0.17)	1.99	0.0495	1.16 (0.08)	0.82	0.4138
Texas High Plains	0.44 (0.17)	0.90	0.3712	1.10 (0.08)	0.20	0.8401
North central Oklahoma	0.47 (0.11)	1.69	0.0946	1.06 (0.06)	−0.43	0.6665
Overall (Inc. central Kansas)	0.29 (0.07)	3.98	0.0001	1.09 (0.05)	22.67	0.0001

decision made from a sample from a single 8.1-ha unit would be sufficient for making a pest management decision for a 16.2-ha management unit. We also calculated Wilcoxon tests to compare the number of caterpillars per panicle among the two 16.2-ha blocks within the same field. There was one significant Wilcoxon test for the eight fields in which we sampled two 16.2-ha blocks. Although the number of comparisons is probably too few to be definitive, evidence suggests that sampling a single 16.2-ha block provides sufficient information for making a management decision for a larger field. There was little evidence to suggest that oviposition by moths in sorghum fields was aggregated at scales of 8.1–16.2 ha, resulting in approximately equal density of panicle worms among blocks of those sizes within fields. The practical significance of the two results was that sampling only a portion of a field, as normally occurs in the process of sequential sampling, would justify decisions applied to a larger area within the field, and perhaps to the entire field. Because 16.2-ha blocks were usually not contiguous within a field, the limited data suggest that results from sampling from one 8.1-ha block would frequently provide reliable decisions for a field at least 32.4-ha in area.

Developing a Sequential Sampling Plan. The homogeneity of slopes regression model for Taylor's power law was significant ($F = 311.5$; df = 7, 96; $P < 0.0001$). The regression model explained most of the variation in the relationship between $log(s^2)$ and $log(\bar{X})$ at $R^2 = 0.96$. There was very little evidence for difference in *log*(a) or b among the four regions (Table 1). The only significant difference was for the intercept (*log*(a)) for the Texas Coastal Plains region. In all other cases, parameters were not significantly different among the geographic regions. Thus, there was little evidence for difference in spatial distribution of panicle caterpillars in sorghum fields among regions, thus indicating that sampling effectiveness and error rates associated with population estimation would be similar among regions using a single sequential sampling plan constructed from data from all regions.

The average of the variance of counts of caterpillars per panicle for the 103 fields (mean of $s^2 = 1.57$, SE = 0.51) was greater than the average of the mean of counts (mean of $\bar{X} = 0.42$, SE = 0.05), suggesting existence of an aggregated distribution of counts. The presence of an aggregated distribution was confirmed by the approximate chi-square test based on the index of dispersion (Elliott 1977) for the 103 samples ($\chi^2 = 11058.0$; df = 4841; $P < 0.001$).

Pearson's chi-square statistic for lack of fit to the negative binomial distribution was calculated for each sampled field. Of tests for 103 fields, seven showed a significant lack of fit to the negative binomial distribution. Seven significant tests of 103 was close to the number expected by chance when testing at a significance level of $\alpha = 0.05$. Thus, the result supported the conclusion that the negative binomial distribution was an acceptable probability model for counts of caterpillars per sorghum panicle.

An unweighted regression through the origin of y_i against x_i for samples from the 103 sorghum fields was significant and had a slope of 2.74 ($k_c = 0.365$; Table 2). A weighted regression using an estimate of $k = 0.365$ in calculating Bliss and Owens' (1958) weights yielded $k = 0.471$, but a much smaller r^2 than the unweighted regression. Iterating on the weighted regression changed k_c only slightly from the value for the first weighted regression, with correspondingly small values for r^2. The greater r^2 associated with the unweighted regression combined with the relatively small change in k_c from iterative weighted regressions led us to conclude that $k_c = 0.365$ was the best estimate. Using the Bliss and Owens' (1958) test procedure for the acceptability of a common *k*, the *F*-test associated with the slope was significant ($F = 55.75$; df = 1, 99; $P < 0.001$), whereas the *F*-test for existence of a nonzero intercept was not significant ($F = 0.12$; df = 1,99; $P > 0.500$). Hubbard and Allen (1991) found that selecting an estimate of k_c smaller than the true value resulted in more conservative error rates than those specified in the SPRT (α and β), and the effect on ASN and OC caused by misspecification of *k* was small. Shah et al. (2009) observed larger effects on ASN and OC from misspecification of *k*, but the magnitude of the misspecification of *k* in their study was

Table 2. Statistics for regression models to estimate the parameter *k* of the negative binomial distribution for samples from 103 sorghum fields consisting of counts of caterpillars on 48 panicles

Model	Slope (SE)	*k*	r^2	F	*P*
Unweighted	2.74 (0.36)	0.365	0.36	56.81	<0.0001
1st weighted	2.12 (0.68)	0.471	0.09	9.85	0.0022
2nd weighted	2.11 (0.68)	0.474	0.09	9.70	0.0024
3rd weighted	2.11 (0.68)	0.475	0.09	9.70	0.0024

All regressions were forced through the origin. Degrees of freedom were 1 for model (numerator) and 101 for error (denominator) in all regressions.

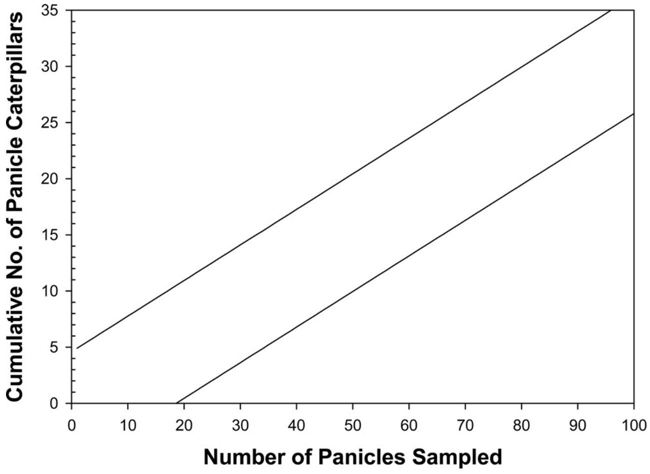

Fig. 3. Sequential sampling stop lines for sampling panicle caterpillars in sorghum for an economic injury level of 0.5 caterpillar per sorghum panicle.

much greater than was likely for our data. Therefore, the hypothesis of a common *k* was not rejected (Bliss and Owens 1958) and developing SPRT for a negative binomial distribution with $k_c = 0.365$ was justified.

The economic injury level for panicle caterpillars depends on yield, crop value, and size of the caterpillars infesting a sorghum field (Knutson and Cronholm 2007). We constructed a sequential sampling plan based on SPRT for an economic threshold of 0.5 caterpillars per panicle, which is typical of economic thresholds for panicle caterpillars (Knutson and Cronholm 2007). We chose a safe level of 0.20 caterpillars per panicle, which was set at less than half the economic threshold. The data set of 0.02–3.17 medium and large worms per panicle observed in the field encompassed these thresholds. Stop sampling lines for panicle caterpillar sequential sampling in sorghum for an economic injury level of 0.5 caterpillars per sorghum panicle are illustrated in Fig. 2. The lower stop line does not permit a "do not treat"' decision until a minimum of 18 panicles are inspected, even if no panicle worms are detected. Based on the upper stop line, a treat decision can be made after inspecting a single panicle, but a decision based on such a small sample would probably not be advisable. At >0.45 caterpillars per panicle, the average number of panicles inspected to make a decision was less than the current recommendation of 30 (Fig. 3). At densities <0.12 caterpillars per panicle, average sample sizes were also <30 panicles. For densities between 0.13 and 0.41 caterpillar per panicle, >30 panicles must be inspected on average to make a management decision. It is worth noting that the fixed sample size of 30 panicles was set in the literature without specifically known statistical characteristics, as can be set when comparing sequential plans to single (fixed) sampling plans, and the sample savings may be greater if the fixed plans were designed with specific statistical criteria comparable with the sequential plans (Guenther 1977, Brewer and Trumble 1991). This indicates that the currently recommended fixed sample size of 30 panicles frequently does not have error rates equivalent to those specified in the sequential sampling plan when populations are near the economic threshold of 0.5 caterpillars per panicle. The plan improves on currently recommended sampling procedures for panicle caterpillars because fewer samples are required at low and high densities, and error rates are improved at intermediate densities, where a larger number of samples are required to make decisions with acceptable error rates. If so desired, the parameters α, β, μ_o, and μ_1 can be manipulated to achieve a sequential sampling plan with more acceptable sampling properties, albeit at the expense of error rates and the magnitude of variation in the estimated population density that can be detected.

Validating the Candidate SPRT. For the 25 sorghum fields sampled for validation, the mean number of caterpillars per panicle in 20 fields was below the safe level of ≤0.20 per panicle, whereas for two fields the mean was >0.20 but <0.35. For the 22 fields with infestations of caterpillars that should result in a no-treat decision, all 22 were correctly classified. For three fields, the mean number of caterpillars per panicle was >0.50, which were correctly classified as needing treatment. No fields were incorrectly classified.

The expected number of samples to make a decision was generally similar to the observed number of samples (Fig. 4). A linear regression equation fitted to the data had a slope of 0.95, which was not significantly different from 1.0 ($F = 0.88$; df = 1, 23; $P = 0.36$). Furthermore, the intercept was 1.34, which did not differ significantly from zero ($t = 1.00$; df = 1; $P = 0.33$; Fig. 5). Lack of difference from a slope of one and intercept of zero, combined with a large coefficient of determination ($r^2 = 0.93$) indicated strong agreement between the expected number of samples taken from the ASN curve and the number of samples required in practice.

The mean number of panicles inspected to make a decision was 23.9 (SE = 2.40), which was fewer than the current recommendation of 30 samples. Thus, time savings would be expected when using the sequential

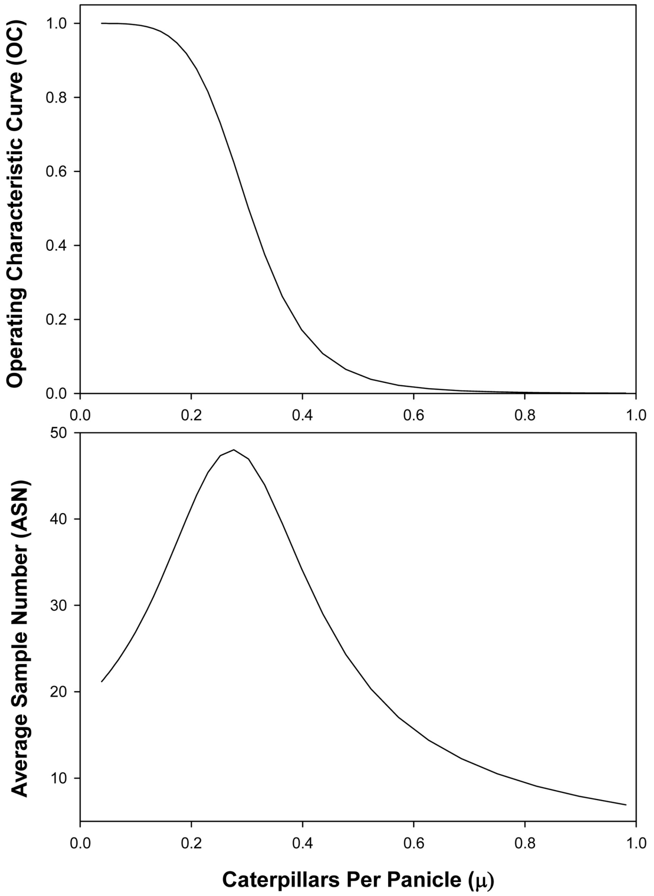

Fig. 4. OC and ASN curves for a panicle caterpillar sequential sampling plan in sorghum with $k = 0.365$, $\alpha = 0.10$, $\beta = 0.05$, $\mu_o = 0.20$, $\mu_1 = 0.50$, and μ ranging from 0.05 to 1.0.

sampling plan. For the three fields where infestations by caterpillars were >0.50 per panicle, 3, 8, and 13 panicles were inspected to make a treatment decision. For these fields, the number of caterpillars per panicle ranged from 0.61 to 1.56 when sampling 48 sorghum panicles. For these circumstances, where treatment would be critical for protecting yield, correct treatment decisions were made with considerable reduction in

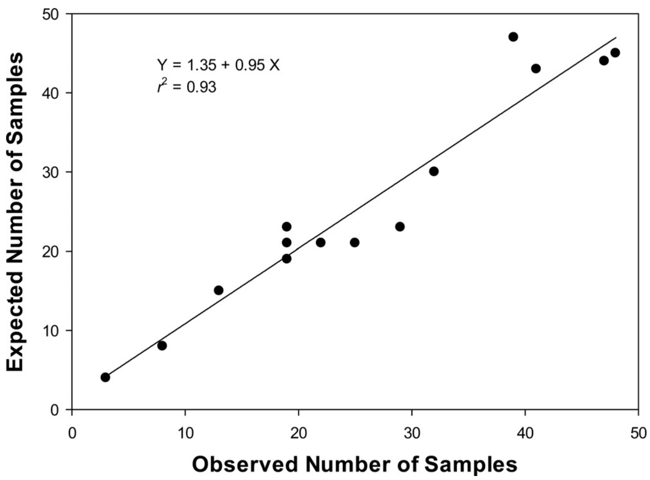

Fig. 5. Expected versus observed number of samples of sorghum panicle caterpillars required to make a treat or a no-treat decision.

sampling effort. Our validation, although not extensive, was accomplished with independent data from fields that differed from those used in developing the plan and were sampled in a different year, which adds further confidence in the relevance of SPRT to a range of field conditions (Vernier et al. 2008). An Internet site has been developed and deployed to aid users in obtaining information needed to implement the sampling methodology (Backoulou et al. 2013). The site provides a tool for calculating the economic threshold for panicle worms, sequential sampling forms for a range of economic thresholds, and instructions on how to sample a sorghum fields for panicle caterpillars. We developed and validated a sequential sampling plan for panicle caterpillar IPM decision-making in sorghum that reduces sampling time compared with the current fixed sample size method of 30 sorghum panicles. Sampling within an 8.1-ha subsection of a field provided density estimates valid for larger areas of at least 16.2 ha, indicating that sequential sampling based on a portion of a field provide decisions that can be applied to a management unit as large as 16.2 ha. The candidate SPRT provided a decision tool dependent on fewer required samples at low and high densities of panicle caterpillars at known acceptable fixed error rates, whereas a larger number of samples were required to make decisions with the same acceptable error rates when densities were near the thresholds.

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