STORED-PRODUCT AND QUARANTINE ENTOMOLOGY

Acoustic Counting of Adult Insects with Differing Rates and Intensities of Sound Production in Stored Wheat

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ABSTRACT Automated acoustic detection systems count the insects in a grain sample by analyzing the spatial and temporal distribution of sounds. The acoustic location fixing insect detector is an automated system developed originally to quantify hidden larval infestations in 1-kg samples of wheat. The detector analyzes input from an array of sensors embedded in the sample container walls. It identifies (scores) a specific pattern of input as an insect if the spatial and temporal distribution matches the criteria based on a calibration with 4th-instar rice weevil, *Sitophilus oryzae* (L). However, expanded testing has revealed considerable differences in the spatial and temporal distributions of sounds made by insects of different species and sizes. These differences were examined in a series of tests with insects that range an order of magnitude above and below the 1.5-mg weight of the *S. oryzae* larvae. A particular focus was the detection order of the first 2 sensors registering each sound. Multiple sounds from an insect tend to cluster together into a small number of contiguous 1st:2nd sensor detection pairs, but the pattern for background noises is random. It was determined that the cluster size, the number of contiguous 1st:2nd detection pairs, was proportional to insect weight. The rate of sound detection was inversely proportional to weight. Thus, to reliably count insects with widely varying sound production patterns, the sound pattern identification algorithm needs to self correct, depending on the input received from the grain sample. Adults or larvae generating large numbers of loud sounds, typically weighing >1 mg, can be scored in a few seconds, but those generating small numbers of weak sounds, typically <1 mg, should be monitored for periods >10 min. The possibility of using differences in cluster size to distinguish among species is also discussed.

KEY WORDS *Cryptolestes ferrugineus, Oryzaephilus surinamensis, Rhyzopertha dominica, Sitophilus oryzae, Tribolium castaneum,* sound detection

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THE MOST COMMON method of inspecting commercial grain for insects is to sieve representative samples (FGIS 1989, Manis 1992). For quality control, sieving is often augmented with relatively expensive, x-ray radiography (Milner et al. 1950, Schatzki and Fine 1988). Recent advances in acoustics and digital signal processing have fostered interest in acoustic detection as an automated, alternative inspection technology (Fleurat-Lessard et al. 1994, Hagstrum et al. 1996, Mankin et al. 1996, Reichmuth et al. 1996).

The effective use of acoustic technology for grain sample inspection requires a quantitative understanding of several physical and biological factors that affect sound production, distribution, and detection. The physical factors include the intensity, duration, and spectral characteristic of the sound at the source, the distance to the receiver and the receiver's spectral sensitivity (Beranek 1988, Forrest and Raspet 1994), the acoustic attenuation of the transmitting medium (Hickling and Wei 1995), and the temporal and spectral pattern of background noise (Mankin et al. 1996). The biological factors include species-specific physiology and behavior, temperature (Shade et al. 1990, Hagstrum and Flinn 1993), and grain type and quality (Vick et al. 1988a, b).

Many of these factors were addressed initially in a series of quantitative studies by Webb et al. (1988), Hagstrum et al. (1988), and Vick et al. (1988a, b). It was shown that in an acoustically shielded environment, the intensity of sounds made by insects in grain and the sensitivity of commercially available sensors was sufficient for construction of a reliable automated detection system. The number of sounds detected in a grain sample was proportional to the number of larvae of the lesser grain borer, *Rhyzopertha dominica* (F.) (Bostrichidae), the rice weevil, *Sitophilus oryzae* (L.) (Curculionidae), or the Angoumois grain moth, *Sitotroga cerealella* (Olivier) (Gelechiidae), infesting the sample. Subsequently, Hagstrum et al. (1990, 1991, 1996) took advantage of this proportionality to monitor changes over time in populations of *R. dominica, S. oryzae,* and the red flour beetle, *Tri-*

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bolium castaneum (Herbst) (Tenebrionidae), in stored wheat.

The effect of ambient noise on the accuracy of automated acoustic detection systems was considered by Vick et al. (1988a) and Mankin et al. (1996). The latter compared the sound pressure levels of sounds made by *S. oryzae* larvae with background noise levels in commercial grain elevators. The weakest detectable larval sounds, <20 dB referenced to 20 μPa, were comparable in intensity, duration, and spectral pattern to grain-settling noises. These signals were 40–60 dB below background levels commonly found in commercial grain elevators. Both studies confirmed that the problems of external background noise could be reduced by constructing enclosures from inexpensive materials that provided 60–80 dB attenuation.

Several reports have considered the effect of insect size on sound production. Vick et al. (1988b) determined that the relative amplitude of sounds made by *R. dominica*, *S. oryzae*, and *S. cerealella* larvae was proportional to head capsule size, which correlated with weight. Similarly, Shade et al. (1990) found that the probability of detecting a *Callosobruchus maculatus* (F.) (Bruchidae) larva was proportional to its size. Hagstrum and Flinn (1993) found that the rate of sound production by adult *S. oryzae*; *T. castaneum*; *R. dominica*; rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) (Cucujidae); and sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.) (Silvanidae), was proportional to insect weight.

To minimize effects of variation in the intensity and rate of insect sounds on insect quantification, Shuman et al. (1993) developed an acoustic location fixing insect detector that counted the number of separate sound sources in a grain sample. Although the initial test of the detector focused on the feasibility of quantifying hidden infestations of 4th-instar *S. oryzae* (Shuman et al. 1993), the results suggested the potential for automated inspection of grain samples containing larvae or adults of a broad size range. This was because the background noise in grain samples was distributed randomly, whereas larval sounds, originating from specific kernels, were distributed nonrandomly. Sounds generated by any insect would be expected to distribute nonrandomly across a sensor array. The problem of scoring a set of sounds as insects or noise thus becomes a problem in statistics.

To characterize differences between insect sounds and background sounds in a practical context, we conducted a series of tests comparing the distributions of sounds from different sized insects with the distribution of background noise in wheat samples. Tests were done with adult *C. ferrugineus, O. surinamensis, R. dominica, S. oryzae,* and *T. castaneum,* 5 common stored-grain Coleoptera (Campbell and Sinha 1976, Storey et al. 1982) ranging in weight from 0.2 to 2.6 mg. Because the minimum sample inspection period is of applied interest, we estimated the minimum time for scoring each species. We also considered differences among sound clusters that potentially can be used to distinguish among species.

Materials and Methods

Acoustic System. The detection unit (Shuman et al. 1993) contained 16 piezoelectric sensors mounted along one wall of a 1-kg sample container. The top and bottom ends of the container opened to load and unload grain. When a sound exceeded a preset amplitude threshold, T_a, the unit signaled a digital input/output board in a microcomputer (Shuman et al. 1993), timed the beginning of the sound, and registered the 1st and 2nd sensors to detect the signal. If the sound was detected only at 1 sensor, (e.g., x) and was too weak to be detected at an adjacent sensor the 1st:2nd sensor detection pair was specified as x:x, where $0 \leq x \leq 15$. Each sound thus was characterized by a time of occurrence and 1 of 46 different detection pair combinations (see Table 1). Sounds made by an insect usually fell within a cluster of contiguous 1st:2nd sensor detection pairs.

Insect Rearing and Handling. Adult insects (1–2 wk old) were obtained 1 d before a test from laboratory colonies cultured in 946-ml jars at 26 ± 1°C, 54 ± 5% RH, and a photoperiod of 14:10 (L:D) h. *T. castaneum* was reared on whole wheat flour, cornmeal, and brewers' yeast (0.465:0.465:0.07 proportions by weight, respectively). *S. oryzae* and *R. dominica* were reared on soft red winter wheat and yeast (0.992:0.008, respectively). *O. surinamensis* was reared on rolled oats and yeast (0.971:0.029, respectively). *C. ferrugineus* was reared on cracked wheat, rolled oats, and yeast (0.475:0.475:0.05, respectively). Trials were conducted in an anechoic chamber (Vick et al. 1988b) at 26 ± 1°C.

For each trial, the detector was suspended from the ceiling of the anechoic chamber and filled with a separate, 1-kg sample of uninfested wheat. If the trial was not a control, the unit first was filled up to the level of a randomly chosen sensor. A single adult beetle was placed on the surface near the center axis, and then the remainder of the 1-kg sample was added. The trials began 3 min after grain loading. Testing continued 3 min for *O. surinamensis, C. ferrugineus,* and uninfested controls, but only 1 min for *S. oryzae, T. castaneum,* and *R. dominica* because the number of counts greatly exceeded the minimum levels of detectability. Ten trials with different individuals were run daily, with 30 trials total for each species and the uninfested controls. Formal trials were not done with multiple insects because preliminary experiments confirmed the results of Shuman et al. (1993). The system easily distinguishes among detectable insects unless their positions closely overlap.

Analysis of Sound Count Distributions. The criterion for distinguishing an insect from the background is based on the expected distribution

Table 1. Numbers of sounds registered in different 1st:2nd sensor detection pairs in ten 3-min trials with adult *S. oryzae*

1st:2nd sensor order	No. sounds in trial, T#, with insect near sensor x ($0 \le x \le 15$)									
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
0:0	0	**4**	0	0	0	0	0	1	0	0
0:1	0	**63**	0	0	0	0	0	0	0	0
1:0	0	**40**	0	0	0	0	0	0	0	0
1:1	0	**66**	0	0	0	0	0	0	0	0
1:2	0	**43**	0	0	0	0	0	0	0	0
2:1	0	**5**	0	0	0	0	0	0	0	0
2:2	0	**2**	0	0	0	0	0	0	0	0
2:3	0	0	0	0	0	0	0	0	0	0
3:2	0	**4**	2	0	0	0	0	0	0	0
3:3	0	**6**	0	0	0	0	0	0	0	**20**
3:4	0	0	0	0	0	0	0	0	**2**	**51**
4:3	0	0	0	0	0	0	0	0	**3**	**35**
4:4	0	2	0	0	0	0	0	4	**74**	**28**
4:5	0	0	0	0	0	0	1	0	**83**	**16**
5:4	0	0	0	0	0	0	0	0	**334**	**10**
5:5	0	0	0	0	0	0	1	1	**122**	**8**
5:6	0	0	0	0	1	0	0	0	**181**	0
6:5	0	0	0	0	0	0	0	**2**	**61**	0
6:6	0	0	0	0	0	0	1	**8**	**0**	0
6:7	0	0	0	0	0	0	0	**61**	**4**	0
7:6	0	0	0	0	0	0	0	**96**	**5**	0
7:7	0	0	0	0	**2**	0	0	**123**	0	1
7:8	0	0	0	0	**3**	0	0	**58**	1	0
8:7	1	0	0	0	**195**	1	0	**26**	1	0
8:8	0	0	2	0	**385**	1	0	**10**	1	0
8:9	0	0	0	0	**621**	1	0	**4**	0	0
9:8	0	0	**1**	0	**52**	3	0	**1**	0	0
9:9	0	0	**1**	0	**23**	0	0	**4**	1	0
9:10	0	0	**5**	0	0	**9**	0	0	0	0
10:9	0	1	**28**	1	0	**48**	1	1	0	0
10:10	0	1	**81**	0	0	**236**	0	0	0	0
10:11	0	0	**46**	**3**	0	**282**	0	0	1	0
11:10	0	0	**11**	**28**	0	**87**	0	0	0	0
11:11	0	0	**4**	**98**	0	**9**	0	1	0	0
11:12	0	0	**1**	**123**	0	**13**	**4**	0	0	0
12:11	0	0	0	**43**	1	**3**	**23**	0	0	0
12:12	0	0	3	**16**	0	**1**	**188**	0	0	0
12:13	0	0	0	**6**	0	**1**	**226**	0	0	0
13:12	0	0	0	**1**	0	0	**73**	0	0	0
13:13	1	0	0	**1**	0	0	**17**	0	0	0
13:14	0	0	0	0	0	0	**3**	0	0	0
14:13	**2**	0	0	0	0	0	0	0	0	1
14:14	**2**	0	1	0	0	0	0	0	0	1
14:15	**6**	0	0	0	0	0	0	0	0	0
15:14	**131**	0	0	0	0	0	0	0	0	0
15:15	**282**	0	0	0	0	0	0	0	0	0

Counts boxed in thick lines indicate clusters scored as insects in each trial. Double thin lines designate insect position.

of random noise events among 1st:2nd pairs, the discrete Poisson distribution (Box et al. 1978, Cox and Lewis 1978). The estimated mean number of random sounds is $\mu = \ln (N_T/N_0)$ (Steel and Torrie 1960), where N_T is the total number of detection pairs sampled (30 trials × 46 1st:2nd pairs = 1380), and N_0 is the number of pairs with 0 events. The goodness-of-fit between the observed and the Poisson distribution was estimated by the chi-square test(Steel and Torrie 1960).

The observed probability of 2 random noises occurring at adjacent pairs was compared with the probability estimated from the binomial distribution (Box et al. 1978). The estimated probability of 2 random noises registered at adjacent sensor detection pairs is $P[(1)] = P(1) \times P(1)$, where $P(1)(1)$ is the probability of 1 noise occurring at a 1st:2nd detection pair during a 3-min trial. The estimated probability of 2 noises occurring at one pair and 1 at an adjacent pair during a trial was estimated as $P[(2)(1)] = P(2) \times P(1)$.

Analysis of Sound Count Intervals. The mean interval between insect sounds provides a measure of the sampling duration needed to ensure correct scoring. Sound count intervals were analyzed by SAS PROC means and PROC general linear model(GLM) (SAS Institute 1988) for *T. castaneum*, *S. oryzae*, and *R. dominica*, the 3 species that had counts in every trial. Because *C. ferrugineus* and *O. surinamensis* adults were not always scored during 3-min trials, the sampling period, n, needed to score insects at confidence levels, $CL = 0.5$, 0.9 or 0.95, was estimated from the Poisson equation (Steel and Torrie 1960): $n = -\ln(1 - CL)/\mu_s$, where μ_s is the mean scoring rate.

Analyses of Cluster Differences Among Species. Analyses of variance were done in SAS (SAS Institute 1988) on total count, interval between counts, peak count (largest count at a single 1st:2nd pair, and cluster size (number of contiguous pairs with nonzero counts). Means were compared using the Waller-Duncan k ratio t-test (SAS Institute 1988). To examine the effect of insect size on cluster size, 25 adults of each species were weighed individually, and the regression of cluster size on mean weight was calculated by SAS PROC GLM (SAS Institute 1988). Lack of fit to the regression was calculated as specified in Box et al. (1978).

Results and Discussion

Analysis of the distributions of sound counts among 1st:2nd sensor detection pairs revealed differences from the background noise distribution that could be used to score insects of all 5 species. The major difference among species was in the duration of monitoring needed to ensure an accurate score. We first consider the sound count distributions, which were used to modify the algorithm originally used by Shuman et al. (1993) to score *S. oryzae* larvae. The algorithm is applied in the scoring of individuals of the different species. The scoring results are then considered in the context of grain inspection programs.

Distribution of Sound Counts Among 1st:2nd Detection Pairs. In an ideal detection system, all

Table 2. Predicted and actual count distribution of 1st:2nd detection pairs for controls compared with *C. ferrugineus* and *O. surinamensis*

No. counts in single, [], or adjacent, [][] . . . , 1st:2nd pairs	Distribution of counts for Predicted control	Actual control	*C. ferrugineus*	*O. surinamensis*
[0]	1,199	1,199	1,101	1,060
[1]	169	165	225	224
[2]	12	14	40	46
[3]	1	2	4	8
[4]	0	0	5	10
[5]	0	0	2	4
[>5]	0	0	0	28
[1] [1]	19	14	30	23
[2] [1]	3	3	7	4
[>2] [1]	0	0	2	3
[>2] [2]	0	0	2	0
[1] [1]; [1]	2	1	3	3
[2] [1] [1]	0	1	3	1
[>2] [2] [2]	0	0	2	3
[>0] [>0] [>0] [>0]	0	0	1	10

Table 3. Comparison of scoring and cluster size in trials with 1 adult of different species

Species	% trials with insect score of 0	1	2	Mean cluster size ± SE
C. ferrugineus	70	30	0	3.30 ± 0.42
O. surinamensis	43	54	3	5.11 ± 0.48
R. dominica	0	97	3	6.87 ± 0.33
S. oryzae	0	93	7	8.96 ± 0.48
T. castaneum	0	97	3	10.50 ± 0.62

All means of cluster size (the number of adjacent signal detection order combinations with nonzero counts) were significantly different by the Waller–Duncan *k* ratio *t*-test (minimum significant difference = 1.43).

sounds made by a single insect are detected at a single 1st:2nd detection pair, but the sounds detected in actual trials fall into clusters such as those in Table 1 for several reasons. Sounds initiated at different positions may take divergent paths at different velocities through the heterogenous air-grain medium. Also, nonuniformity in the spectral sensitivity of piezoelectric sensors and variability of spectral and temporal characteristics of individual sounds cause variation in the time when a signal first passes an amplitude threshold. The cluster size increases as the intensity of the sounds increases because sensors farther away can detect the signal. However, if sounds occur at a sufficient rate, the clusters can be statistically distinguished from the random background. *T. castaneum, S. oryzae* (see Table 1), and *R. dominica* made frequent, loud sounds in easily identified clusters that enabled rapid scoring. For *C. ferrugineus* and *O. surinamensis,* however, the counts did not exceed background in every 3-min trial though the overall distribution of sounds across 1st:2nd combinations was significantly different from the controls.

The difference from background is shown in Table 2, which lists several elements (e.g., rows [3], [4], [>5], [1][1], and [>2][2][2]) where the controls followed the Poisson distribution, but not the infested samples. The *C. ferrugineus* distribution, for example, deviated from the Poisson distribution by $\chi^2 = 9.46$, df = 3, $P < 0.01$. Counts are listed in Table 2 only for *C. ferrugineus* and *O. surinamensis* because the distributions for *S. oryzae, R. dominica,* and *T. castaneum* were obviously nonrandom. The control was not significantly different from the Poisson distribution (μ = 0.140596, $\chi^2 = 1.43$, df = 3, $P > 0.25$).

Insect Scoring Algorithm. The distribution of random noises in the control trials (Table 2) was used to construct the following algorithm for scoring the correct number of insects in the sample container: the count at a single 1st:2nd pair must be >4, or >2 counts must occur at adjacent pairs, or counts must occur at ≥5 adjacent pairs, i.e., T_c = [>4] or [>1][>1] or [>0][>0][>0][>0][>0]. With this algorithm, the control samples scored no insects, but inspection of the distributions of sounds made by large insects revealed several tests where a single cluster was split into 2 separate clusters separated by a single 1st:2nd pair with a 0 count. This problem was largely solved by adding an additional criterion: if 2 clusters are separated by a pair with 0 counts, but the count at one or both of the ending pairs between the 2 clusters exceeds T_C, the clusters are merged.

Minimum Sampling Durations Required to Score Different Species. Based on the algorithm above, individual *T. castaneum, S. oryzae,* and *R. dominica* adults always made enough sounds to be scored as ≥1 insect within a 1-min trial period (Table 3). To estimate the maximum necessary sampling time, we analyzed the intervals between counts at a given 1st:2nd combination for 10 randomly chosen trials of each insect. The maximum interval between counts was only 9.56 s (for *R. dominica*) and the mean ± SE interval between counts was 0.228 ± 0.009, 0.103 ± 0.003, and 0.061 ± 0.001 s for *R. dominica, S. oryzae,* and *T. castaneum,* respectively.

By contrast, *O. surinamensis* adults were scored in only 57 ± 8% of the 3-min trials (1 score per 1.8 min) and *C. ferrugineus* in 30 ± 12%, (1/3.3 min). The distributions that resulted in these scores are listed in Table 2. *O. surinamensis* had 32 occurrences of 1st:2nd detection pairs with counts [≥5] and 17 of [≥3] in size. *C. ferrugineus* had 2 occurrences of [5], 2 of [>2,2], and 2 of [≥3]. The trial durations needed to score 50, 90, and 95% of *C. ferrugineus* were 7, 22, and 28 min. The corresponding durations for *O. surinamensis* were 3, 12, and 16 min. These insects can be counted accurately, but higher precision comes at the cost of longer monitoring periods. At a commercial elevator, it may be possible to decrease the periods by increasing the temperature of the grain sample (Shade et al. 1990, Hagstrum and Flinn 1993), particularly in cool weather.

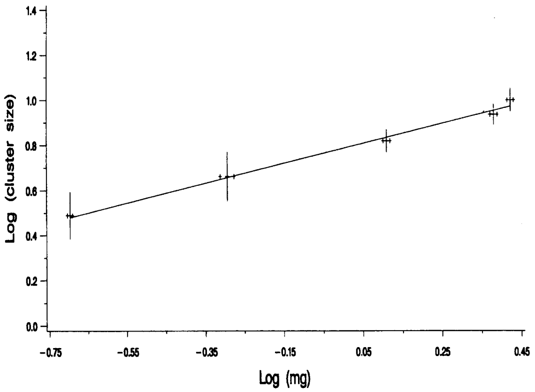

Fig. 1. Relationship between mean weight and cluster size of sounds by adults of different species. Standard errors of cluster size and weight are shown as vertical and horizontal bars, respectively, centered on the means.

Cluster Differences Among Species. Many of the measurements on clusters, including the total count, interval between counts, peak count, and the cluster size, exhibited differences among species in 3 replications of 10 random trials. The means for total count and interval between counts could not be used to distinguish among all species because of the large intertrial variation (e.g., $F = 166$; df = 2, 27; $P < 0.0001$ for interval between counts). Cluster size, however, was significantly different among all species (Table 3) by the Waller–Duncan k ratio t-test, and significantly different from the control by the Student t-test (SAS Institute 1988).

The underlying basis for the differences of cluster size among species is the difference in signal strength, which is proportional to weight (Vick et al. 1988b, Shade et al. 1990, Hagstrum and Flinn 1993). Although distance affects signal strength, the effect of distance is averaged over multiple tests. Fig. 1 shows the regression of cluster size on mean weight: log (cluster size) = 0.79 + 0.44 × log (weight), with $n = 118$, $r^2 = 0.50$, $SE_{Intercept} = 0.02$, $SE_{Slope} = 0.04$ and $MSE = 0.02$. The lack of fit was not significant ($F = 0.005$; df = 3, 113; $P > 0.4$). These differences among species are of practical interest due to the need for automated distinguishing of species in pest management programs (e.g., Hagstrum et al. 1996, Hagstrum and Flinn 1993).

Some of the differences that occurred among clusters may have resulted from differences in behavior or differences in sound spectra rather than differences in sound intensity. There were many clusters by *O. surinamensis* individuals, for example, where counts were distributed as [>0][>0][>0][>0] but only 1 for *C. ferrugineus*. A trained ear can easily distinguish spectral differences in the sounds made by the different species (e.g., Andrieu and Fleurat-Lessard 1990). Acoustic and digital signal processing technology now is available to use such information in future applications.

Applications of Acoustic Detectors. Although the insects in the current study were adults, the results have significance for the use of acoustic detectors in quantifying hidden larval infestations at commercial grain elevators (Shuman et al. 1993). The 1.5-mg, 4th-instar *S. oryzae* (Kirkpatrick and Wilbur 1965) in the original study made weaker sounds than large adults like *T. castaneum* or *S. oryzae* but louder sounds than smaller larvae or adults of species like *C. ferrugineus*. To score hidden larvae correctly in a grain sample containing other insects of different sizes, a robust algorithm must account for possible differences in sound rate and intensity.

The precision of the insect scoring algorithm is of considerable practical interest because the acoustic location fixing insect detector was developed to automate detection of infestation in grain destined for export. The Grain Inspection Service, Packers, and Stockyard Administration standards for clean and infested grain samples (FGIS 1993) classify 1-kg samples with >1 insect as infested. To avoid misclassifying uninfested grain, it is important that the score not be overestimated when <2 insects are present in the sample. This kind of error occurs primarily as the result of 1 insect being miscounted as 2 (Shuman et al. 1993). Consequently, it is of interest to consider the percentage of overscores associated with the new algorithm. Only 3% of trials with 1 adult *O. surinamensis, R. dominica,* and *T. castaneum* yielded scores >1 (Table 2). The new algorithm correctly classified 97% of the trials in this study as uninfested (see Table 2), which indicates that the system has potential for high precision.

Differences in the accuracy of the algorithm were apparent in trials with different species. The low probability of overscoring large insects in a sample came at the expense of underestimating the scores of *C. ferrugineus* or *O. surinamensis* adults. Adult *C. ferrugineus* (0.2 mg in weight) and *O. surinamensis* (0.5 mg) required sampling durations estimated at >10 min for 90% to be scored as insects in a 1-kg wheat sample. Fourth-instar, 1.5-mg *S. oryzae* required 9-min trials for 70% of the insects to be scored (Shuman et al. 1993), and 3rd instars require even longer for accurate scoring (unpublished data). By contrast, the larger adults, *R. dominica, S. oryzae,* and *T. castaneum,* were scored within a few seconds. Potentially, the detection precision can be improved by decreasing the sampling duration in proportion to the number of counts. Samples with only a few sounds should run for longer periods to maximize the likelihood of detecting larvae or small adults. The longest duration that adapts easily to current grain sampling procedures is ≈20 min.

Comparisons with Other Acoustic Detection Technology. Like the acoustic detector, other detection techniques such as x-ray imaging (Schatzki and Fine 1988) and nuclear magnetic resonance spectroscopy (Chambers et al. 1984) also detect large insects more easily than small ones. It is difficult to detect small adults or larvae younger than 3rd instar in large grain samples by any known technique. For acoustic detection, the problem is one of signal-to-noise ratio. *S. oryzae* larvae, for example, generate 23-dB signals referenced to 20 μPa (Mankin et al. 1996), and many grain-settling sounds are comparable in intensity. Overall noise backgrounds, even in a laboratory, are usually >50 dB sound pressure level, so the grain samples must be shielded if larvae are to be detected. Adult *T. castaneum* or *R. dominica* are 10–100 times louder than larvae (Hagstrum et al. 1990, 1991), but *C. ferrugineus* and *O. surinamensis* adults make sounds comparable to those of *S. oryzae* larvae.

The benefits of quantifying insect infestations by distributional analyses are seen by comparison with the study of Hagstrum and Flinn (1993), which used the same sensors and insects but summed all sounds without localizing the sources. In 10 36-min trials summing the input from 8 sensors, Hagstrum and Flinn (1993) found that the numbers of 10-s intervals with sounds made by individual *C. ferrugineus* in a 1-kg grain sample were not significantly different from background, but the numbers for other species differed from background. The temporal distributions of sounds made by *S. oryzae* and *T. castaneum* could be distinguished from those of *R. dominica*. It should be noted that the localization of sound sources can be achieved to some extent, even without the use of an acoustic location fixing insect detector, by compartmentalizing the sample and analyzing signals in each compartment separately (Hagstrum et al. 1988).

Acoustic detection technology has the potential to solve 2 major problems of the conventional sieving method of inspecting grain (i.e., its inability to detect hidden larval infestations and its labor intensiveness). With a flexible scoring algorithm that adapts to the frequency and distribution of sound production, an acoustic detector can be used for automated counting of both larvae and adults in the 10 to 20 min sampling period currently required to detect larvae. Conventional, labor-intensive inspection methods require 2–20 min to complete, depending on the particular tests being performed, but they do not detect hidden larvae.

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