Automated Acoustical Monitoring of *Tribolium castaneum* (Coleoptera: Tenebrionidae) Populations in Stored Wheat

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ABSTRACT An automated acoustical detection system for monitoring *Tribolium castaneum* (Herbst) populations in stored wheat was evaluated using 16 microphones per 5 bu (176.2 liters) wheat. A regression equation explained 93.9% of the variation in the number of insect sounds over a range of 5–640 adult insects per 5 bu. For one microphone during a 10-s interval, the probability of detection increased rapidly from ≈0.12 with 10 insects per 5 bu to 0.44 with 80 insects per 5 bu, and then more slowly to 0.66 with 640 insects per 5 bu. The probability of detection was ≈0.90 with 40 insects per 5 bu and 3 microphones, 20 insects per 5 bu and 4 microphones, 10 insects per 5 bu and 5 microphones, or 5 insects per 5 bu and 12 microphones. More frequently monitoring a single microphone improved the probability of detection 60–80% as much as adding the same number of microphones. The number of insect sounds was unaffected by the sex or mating status of the insects and decreased logarithmically with increasing distance between insect and microphone. Adults produced 80 times more sounds than larvae. Automation of insect monitoring should increase reliability and reduce labor costs.

KEY WORDS Insecta, stored product, sampling, red flour beetle

MONITORING INSECT POPULATIONS can be a costly part of managing stored grain. Large numbers of grain samples must be taken to detect or estimate insect populations; each grain sample must be sieved, and the sievings must be examined for insects. Because insect populations grow quickly, frequent sampling is required.

A quantitative sampling plan for estimating stored-grain insect population densities using grain triers was reported by Hagstrum et al. (1985). The sampling efforts required to achieve different probabilities of detection or accuracies of estimation were given for a range of insect densities. This sampling model was shown to be applicable to a wide variety of stages and species of insects, sampling devices, grain storage facilities, and types of grain (Hagstrum et al 1988a). These studies indicated that >100 0.5-kg samples per 1,000 bu (35,240 liters) grain are required to be 95% confident of detecting densities of five insects per bushel grain or estimating insect density within plus or minus one insect. Such large sampling efforts should be more practical with automated acoustical detection than with conventional sampling methods.

The ability to detect insect sounds in grain has been demonstrated a number of times (Adams et al. 1953; Bailey & McCabe 1965; Street 1971; Vick et al. 1988; Hagstrum et al. 1988b, 1990). However, the acoustical detection method only recently became practical with enhanced sensitivity of electronic equipment. Hagstrum et al. (1988b) demonstrated that the detection of populations of lesser grain borer, *Rhyzopertha dominica* (F.), larvae feeding inside wheat kernels with a piezoelectric microphone was as accurate as other sampling methods. Tests in 5 bu (176.2 liters) wheat have further demonstrated the feasibility and accuracy of monitoring growing insect populations with a piezoelectric microphone (Hagstrum et al. 1990). These studies also showed that the number of sounds did not differ over a wide range of temperatures or with adult age. A regression equation relating the number of insects to the number of sounds explained 87% of the variation in insect numbers. The strong relationship between insect numbers and insect sounds is the key to using acoustical detection technology for insect monitoring.

This paper reports the evaluation of an automated system for continuous monitoring of *Tribolium castaneum* (Herbst) populations in stored wheat. The probability of detecting insects was determined in relation to insect density, the number of microphones used, and the frequency of monitoring of each microphone. To better understand some of the factors that could influence the relationship between the number of insect sounds and the number of insects, the effects of insect sex, mating status, and the distance between insects and microphones were studied.

Materials and Methods

Tests were conducted with 5, 10, 20, 40, 80, 160, 320, and 640 *T. castaneum* adults per 5 bu (176.2 liters) hard red winter wheat. The wheat had 12% moisture, was placed in a 55-gallon (208 liters) steel drum, and was kept at 25°C. Four cables, each with

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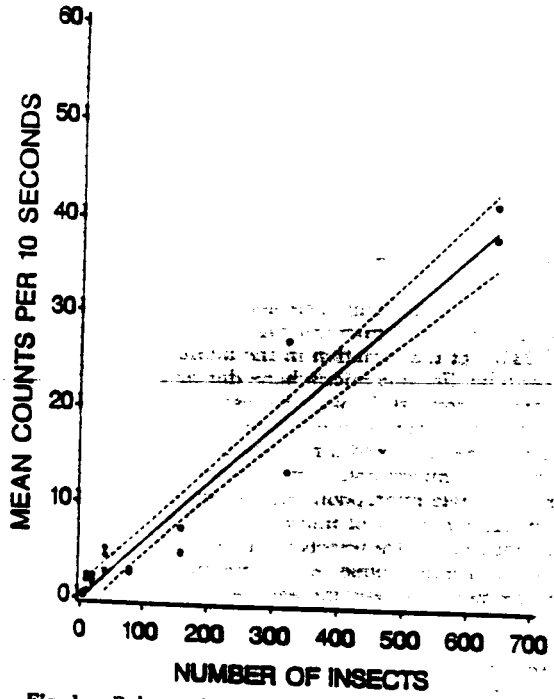

Fig. 1. Relationship between insect density per 5 bu (176.2 liters) wheat and the average number of insect sounds counted for a single microphone during a 10-s interval using a frequency counter. The dashed lines show the 95% confidence intervals.

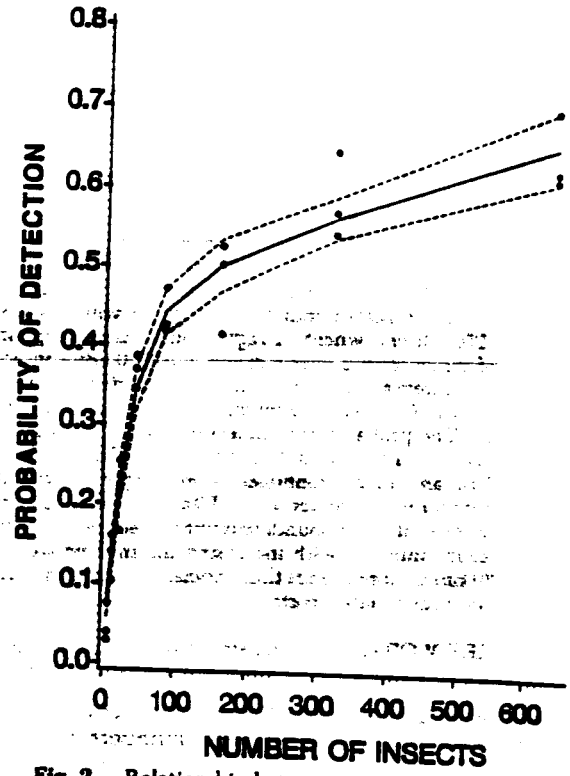

Fig. 2. Relationship between insect density per 5 bu (176.2 liters) wheat and the probability of detecting insects with a single microphone during a single 10-s interval. The dashed lines show the 95% confidence intervals.

four piezoelectric microphones spaced 15 cm apart, were installed vertically in the drum. One cable was placed in the center of the drum and three others were placed at three equidistant locations halfway between the center and the edge of the drum. Insect sounds were monitored for a 24-h period at each insect density using an eight-channel multiplexer (Bruel & Kjaer model 2811, Marlborough, Mass.) to switch between microphones. Because the multiplexer had only eight channels, two 24-h periods were required to monitor all 16 microphones. Each microphone was monitored for 10 s out of every 80 s, or a total of 1,080 times during the 24-h period. The signal from the piezoelectric microphones was amplified (Bruel & Kjaer model 2610) and the numbers of sounds were counted during 10-s intervals (Hewlett Packard universal counter model 5316A, Wichita, Kans.). An IBM-compatible computer stored the data, switched the multiplexer to the next microphone, and reset the counter using software developed by Webb et al. (1988). The test was replicated three times. The probability of detection is the percentage of the times that microphones detected and recorded insect sounds. The number of insect sounds detected per 10-s interval and the probability of detection were regressed on insect density.

Additional data relating the number of insect sounds to sex and mating status of insects and distance between insect and microphone were collected to help better understand the relationship between the number of insects and the number of insect sounds. These tests were conducted in a cardboard cylinder (20 cm high by 4 cm diameter) with a piezoelectric microphone covering the bottom of the cylinder. The effects of sex and mating status on the number of sounds counted was studied with one adult insect in a 2-cm-deep layer of wheat. The effect of distance between insect and microphone was studied by confining a single adult or sixth instar in a cloth bottom cage containing 4 ml of wheat placed on top of the column of wheat. The insects were assumed to be in the center of this 1-cm layer of wheat. The depth of the column was increased by adding 1-cm layers of wheat. With each sex, mating status, or distance, sounds were counted every 10 s for 2 h. The tests with an adult were replicated 20 times and those with a larva were replicated 10 times. An analysis of variance was used to test for significant differences in the number of insect sounds attributable to sex and mating status.

Results

The average number of insect sounds counted per 10-s interval was linearly related to insect den-

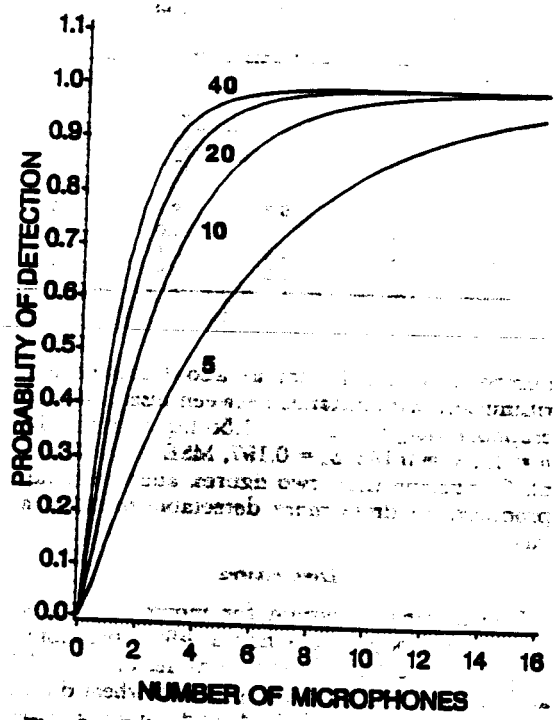

Fig. 3. Relationship between number of microphones and the probability of insect detection. Curves are shown for insect densities of 5, 10, 20, and 40 insects per 5 bu (176.2 liters) wheat.

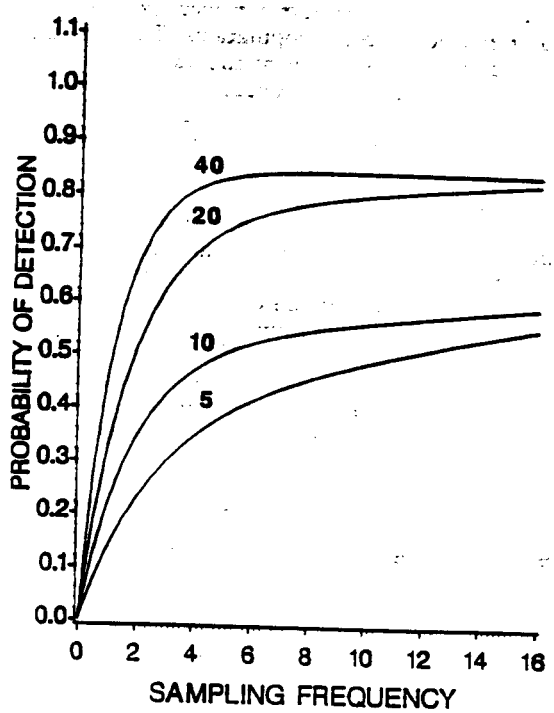

Fig. 4. Relationship between sampling frequency with a microphone and probability of insect detection. Curves are shown for insect densities of 5, 10, 20, and 40 insects per 5 bu wheat.

Table 1. Parameters for regression equations relating number of insect sounds counted to the number of microphones used or the sampling frequency with a microphone at different insect densities per 5 bu (176.2 liters) wheat

Insect density/5 bu	Parameters[a] A	B	C	df	r^2
	Number of microphones				
5	1.03	0.19	—	22	0.9275
10	1.06	0.38	—	22	0.9382
20	1.07	0.59	—	22	0.9304
40	1.04	0.75	—	22	0.9654
80	1.03	0.83	—	22	0.9672
160	1.02	0.87	—	22	0.9753
320	1.01	1.07	—	22	0.9873
640	1.01	1.21	—	22	0.9923
	Sampling frequency				
5	0.38	0.38	0.021	21	0.8945
10	0.49	0.012	0.53	21	0.8465
20	0.76	0.54	0.021	21	0.9819
40	0.85	0.78	−0.0029	21	0.9490
80	0.89	0.85	0.00015	21	0.9500
160	0.88	0.92	−0.0074	21	0.9548
320	0.89	1.19	0.013	21	0.9827
640	0.93	1.30	0.0080	21	0.9936

[a] Coefficients for the double-logarithm model $y = 1 - (A \exp^{-Bx} + (1 - A)\exp^{-Cx})$.

sity ($y = 0.062x - 0.3$, $r^2 = 0.939$, $n = 22$, $S_x = 0.799$, $S_b = 0.00353$, MSE = 9.383) (Fig. 1). The average number of insect sounds counted per 10 s increased from 0.3 with 10 insects per 5 bu wheat to 40 with 640 insects. The regression equation explained 93.9% of the variation in the number of insect sounds counted. The average background count without insects present was 0.35 (SE = 0.019, $n = 17{,}280$).

The probability of detecting insects with a single microphone during a 10-s interval increased with insect density ($y = 1 - 0.56e^{-0.0088x} + 0.44e^{-0.034x}$, $r^2 = 0.967$, $n = 24$, MSE = 0.00159) (Fig. 2). The probability increased rapidly from ≈0.12 with 10 insects per 5 bu to 0.44 with 80 insects, and then more slowly to 0.66 with 640 insects.

The probability of insect detection can be increased by using more microphones (Fig. 3) or by more frequently monitoring a single microphone (Fig. 4). The probability of detection increased rapidly to ≈0.90 with 40 insects per 5 bu and 3 microphones, 20 insects per 5 bu and 4 microphones, 10 insects per 5 bu and 5 microphones, or 5 insects per 5 bu and 12 microphones. More frequently monitoring a microphone improved the probability of detection by roughly 60–80% as much as adding the same number of microphones.

Probability of detection did not increase with insects densities of >40 insects per 5 bu. Parameters for regression equations for curves shown in Fig. 3 and 4 are given in Table 1. These equations explained 89–99% of the variation in probability of detection with the number of microphones or sampling frequency.

Table 2. Frequency distributions of the numbers of insect sounds counted at different insect densities per 5 bu (176.2 liters) wheat

No. sounds/10-s interval	% 10-s intervals by insect density/5 bu								
	0	5	10	20	40	80	160	320	640
0	94.2	95.3	86.6	78.9	63.4	56.2	51.7	41.4	34.4
1–4	3.6	3.2	7.2	12.5	17.9	24.5	19.6	17.9	16.5
5–9	1.1	0.7	2.4	4.0	7.0	10.7	10.4	9.4	7.4
10–19	0.7	0.4	1.7	2.7	6.0	6.2	9.3	9.7	9.5
20–49	0.8	0.8	1.5	1.5	4.5	2.2	7.4	11.0	13.1
50–99	0.1	0.1	0.5	0.3	0.9	0.2	1.4	3.1	8.9
≥100	0	0	0.1	0.1	0.3	0	0.2	7.5	10.2

The average number ($\bar{x} \pm$ SE) of sounds counted for mated males (481 ± 123) and mated females (562 ± 57) were not significantly different (F = 0.18; df = 1, 23; P = 0.67) from those for unmated males (372 ± 25) and unmated females (583 ± 153). Also, there was no significant difference between sexes (F = 2.02; df = 1, 23; P = 0.17). Frequency distributions of insect sounds counted per 10-s interval for different insect densities are shown in Table 2. The frequency distribution for the number of insect sounds counted with five insects per 5 bu wheat is very similar to that when no insects were present. However, for 10 or more insects, the percentages of observations in all frequency classes except the zero class exceeded those in the control. As insect density increased, the zero-frequency class decreased.

The number of insect sounds counted per 10-s interval also varied with the distance between the insect and microphone (Table 3). When insects were within 0.5 cm of the microphone, only 0.8% of the counts were <100. This percentage increased as the distance between insect and microphone increased. The percentages were 31.6, 44.3, 78.3, 84.1, 86.5, 95.2, and 99.1 with distances of 1.5, 2.5, 4.5, 6.5, 10.5, 14.5, and 18.5 cm between the insect and the microphone, respectively. The frequency distributions in Table 2 for densities of 20, 80, and 640 insects per 5 bu are most similar to those in Table 3 for distances of 18.5, 14.5, and 10.5 cm, respectively. The average number of insect sounds counted decreased logarithmically with the distance between adult insect and microphone ($\log_{10}y = 3.16 - 1.74 \log_{10}x$, $r^2 = 0.943$, $n = 21$, $S_e = 0.0969$, $S_b = 0.0987$, MSE = 0.0332) (Fig. 5). The number of counts for larvae also decreased logarithmically with distance between insects and microphone ($\log_{10}y = 1.26 - 1.56 \log_{10}x$, $r^2 = 0.875$, $n = 11$, $S_e = 0.143$, $S_b = 0.197$, MSE = 0.062) (Fig. 6). Comparing these two figures, adults generally produced 80 times more detectable sounds than larvae.

Discussion

The automated system for monitoring stored-grain insect populations had a ≈90% probability of detecting extremely low densities of 5, 10, 20, and 40 adult *T. castaneum* per 5 bu wheat during a 24-h period with 12, 5, 4, and 3 microphones, respectively. These densities are equivalent to 0.04, 0.08, 0.16, and 0.32 insects/kg of wheat. The strong relationship between average number of insect sounds counted and the number of insects indicates that this automated system can accurately estimate adult red flour beetle populations. The fact that increasing the frequency of monitoring of a microphone increased the probability of detection by 60–80% as much as adding the same number of microphones is important. It is much easier and less costly to make additional counts than to add microphones.

The number of counted insect sounds varied with time, distance between insect and microphones, and developmental stage of the insect. Sex and mating status of the insects did not affect the number of insect-produced sounds that were detected. The frequency distributions of the number of insect sounds counted in tests with 5 bu wheat (Table 2) were most similar to those for insects 10.5–18.5 cm from the microphone (Table 3). This similarity

Table 3. Frequency distributions of the numbers of insect sounds counted with different distances between insect and microphone

No. sounds/10-s interval	% 10-s intervals by distance, cm							
	0.5	1.5	2.5	4.5	6.5	10.5	14.5	18.5
0	0	1.7	1.3	47.8	36.1	37.2	55.2	73.1
1–4	0	2.0	3.3	9.6	13.9	18.1	18.9	10.2
5–9	0	1.7	4.8	5.0	8.7	7.6	5.9	3.8
10–19	0.2	3.0	9.8	5.6	8.7	8.9	6.9	5.3
20–49	0	10.0	13.5	6.9	10.0	9.4	4.6	4.9
50–99	0.6	13.3	11.5	3.5	6.7	5.2	3.7	1.8
≥100	99.2	68.4	55.7	21.7	15.9	13.5	4.8	0.9

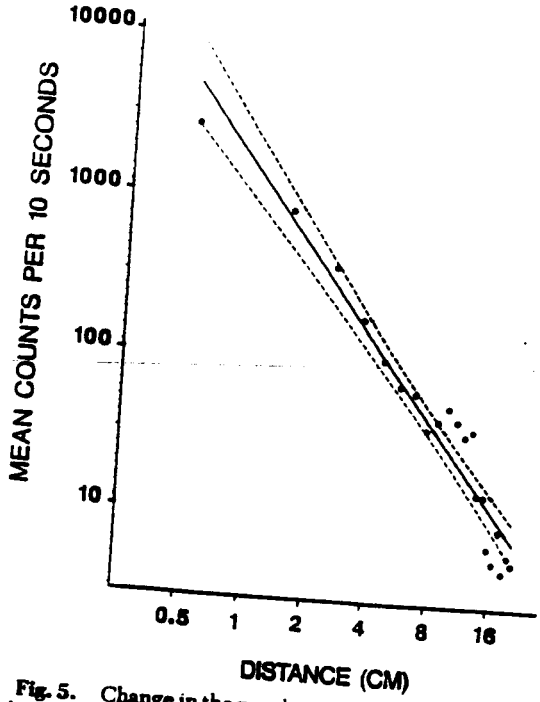

Fig. 5. Change in the number of insect sounds counted per 10-s interval (on a log scale) with increasing distance between single adult insect and microphone (on a log scale). The dashed line shows the 95% confidence intervals.

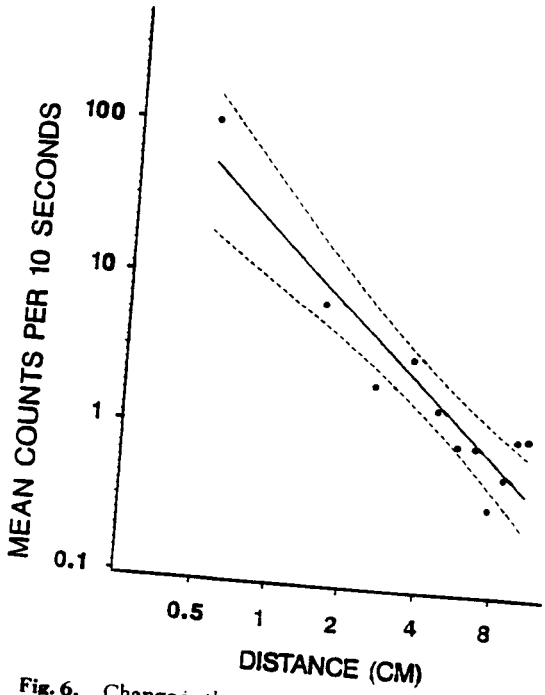

Fig. 6. Change in the number of insect sounds counted per 10-s interval (on a log scale) with increasing distance between single larval insect and microphone (on a log scale). The dashed line shows the 95% confidence intervals.

might suggest that the average distance at which insects are detected by microphones is between 10.5 and 18.5 cm in tests with 5 bu wheat. Adults produced 80 times more detectable sounds than larvae and are therefore more likely to be detected.

This automated system has the potential advantages of detecting sounds of insects feeding and moving around, of monitoring insect populations continuously instead of periodically, and of remote monitoring of all bins at a grain elevator facility from a single computer. This automated system would allow millers to monitor wheat regularly and thoroughly and thus reduce chances that insect populations reach densities resulting in insect fragments in flour above allowable limits. Currently, many infestations are not detected until emergency control with chemical fumigants is the only management option available. By detecting insects earlier and at lower densities, slower acting nonchemical control methods such as aeration can be used. A greater choice of management options could substantially improve grain quality and reduce cost of insect control.

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