AUTOMATED ACOUSTICAL DETECTION OF STORED-GRAIN INSECTS AND ITS POTENTIAL IN REDUCING INSECT PROBLEMS

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Abstract

Acoustical sensors which automatically alert us to the need for insect control can improve pest management by reducing the chances of an infestation going undetected. Also, monitoring of insects in stored grain can be the most costly part of pest management. Acoustical detection may provide a means of continuous, automatic monitoring of insect populations at reduced cost. The potential for automation of insect monitoring with acoustical methods is a major advantage over other methods. Acoustical sensors can provide, without taking grain samples, density estimates of lesser grain borer populations that are comparable to estimates made by counting the number of adults in grain samples. A strong correlation demonstrated between the number of insects and the number of insect sounds is the key to using the acoustical detection method. These studies provide some of the information essential to the development of acoustical detection as a routine method for monitoring stored-grain insect infestations. Applications of the acoustical detection method include a desktop unit for determining the number of insects in grain samples, a probe for estimating the insect populations in stored grain without taking grain samples, and permanently installed cables for monitoring insect populations in the many bins at a grain storage facility from a single computer.

Introduction

Monitoring insect populations is a fundamental part of managing stored grain. Acoustical detection methods were first considered primarily as a means of detecting insects that were feeding inside of the kernels of grain and therefore could not be sieved from the grain and counted. However, the most important contribution of acoustical detection methods may be their potential for automation of insect monitoring. In recent years, much of the information needed for commercial development of acoustical detection has been collected such as the correlation between insect density and number of sounds, the differences in numbers of sounds and detection distances between species and stages of insects, and the temporal variation in insect activity. Also, a number of other factors influencing acoustical detection of insects such as temperature and type of grain have been investigated. Research on the number of grain samples needed to accurately monitor insect populations has increased our awareness of the need to automate insect population monitoring. This paper reviews available information and examines the relevance of this information to commercial development of acoustical detection methods.

Material and Methods

The first studies on acoustical detection of insects used microphones and phonograph cartridges to detect insects feeding inside single kernels of grain (Adams et al. 1953, Bailey & McCabe 1965). More recently high frequency detectors (40 Khz) have been used to study feeding activity of cowpea weevils, Callosobruchus maculatus (F.), inside cowpeas (Shade et al. 1990). These sensors have the advantage of low background sound levels, but are limited by the fact that infested grain must be in contact with sensor. Street (1971) utilized acoustical detection of insects with batches of grain. He mounted 600 wheat kernels to a plastic sheet suspended from a phonograph cartridge. Using rice weevil, Sitophilus oryzae (L.), he could detect one larva-infested kernel in 600. Vick et al. (1988) further increased the volume of grain using a microphone at the base of a sample container holding 100 ml of wheat and could still detect a single lesser grain borer, Rhyzopertha dominica (F.); Angoumois grain moth, Sitotroga cerealella (Oliver); or rice weevil larva. Hagstrum et al. (1988b) inserted piezoelectric sensors into even larger volumes of grain and accurately estimated densities of lesser grain borer larvae without removing grain samples. The piezoelectric sensor has the advantages of 1) high durability which allows sensors to be inserted into grain without damage, 2) being insensitive to the very penetrating low frequency sounds, and 3) low cost. Another way to use the piezoelectric sensor is in probe traps to automatically monitor number of insects captured (Vick et al. 1990). Because the insects in traps are walking on the sensor, insect-produced sounds are much louder than background sounds and the possibility of false positives from background sounds is reduced.

Early studies used earphones or speakers to listen to insect sounds and mechanical counters or strip chart recorders to record insect sounds. Bailey & McCabe (1965) used 16 mechanical counters to record feeding activity of granary weevil, Sitophilus granarius (L.), larvae in 16 wheat kernels. Software developed by Webb et al. (1988) was recently used to automate monitoring of red flour beetle, Tribolium castaneum (Herbst), populations over a 24 h period using 16 of piezoelectric sensors inserted in 136 kg lots of wheat (Hagstrum unpublished). The signal from the piezoelectric sensors was amplified (Bruel & Kjaer Model 2610) and the numbers of sounds were counted during 10 sec intervals (Hewelett Packard universal counter Model 5316A). Only recently have technological advances in sensitivity of electronic equipment made acoustical detection of insects in bulk grain commercially practical.

Results and Discussion

Acoustical detection of stored-products insects was first investigated as a means of detecting insect pest feeding inside of kernels of grain (Adams et al. 1953, Bailey & McCabe 1965, Street 1971, Vick et al. 1988, Hagstrum et al. 1988b). Other nondestructive methods of detecting insects feeding inside of kernels of grain include x-ray of insects within the grain (Milner et al. 1950), measurement of insect-produced carbon dioxide (Bruce et al. 1982), and detection of higher moisture content of insect infested kernels with nuclear magnetic resonance (NMR) spectroscopy (Chambers et al. 1984). Initial cost of the x-ray machine and the ongoing cost of the x-ray film and chemicals to develop it are high and examination of each of the individual grains x-rayed for insects is labor intensive. The cost or labor could be much lower for carbon dioxide, sound and NMR methods than for the x-ray method. X-ray does have the added advantage over carbon dioxide and sound methods of detection of both live and dead insects and identification of the species and stage of insect detected, although eggs and small larvae are generally difficult to distinguish from denser portions of the grain. Also, not all carbon dioxide or sounds detected in grain are produced by insects. Adams et al. (1953) suggested that acoustical detection might be used to monitor "...grain within storage bins for infestation without sampling or removing the grain from the bins, in much the same manner as permanent thermocouple systems are now used for checking the heating of grain in storage." For granary weevil (Fleurat-Lessard & Andrieu 1986), lesser grain borer (Hagstrum et al. 1990) and red flour beetle (Hagstrum unpublished), the effectiveness of acoustical monitoring of insect populations in stored grain without removing grain samples has been demonstrated.

<u>Detection distance</u> - In grain, the number of sounds detected drops off logarithmically with distance of mature rice weevil larvae (Vick et al. 1988) and red flour beetle larvae or adults (Hagstrum unpublished) from the piezoelectric sensor. Adults could be detected readily up to 10 cm away and larvae from only about half that distance. The attenuation of sounds by the grain means that insects from which few sounds are detected when they are close to the sensor will not be detected when they are further away from the sensor. Attenuation also can result in several insects far away from the sensor being mistaken for one insect close to the sensor. There is thus a trade-off between increasing the distance from which insects can be detected and our ability to determine how many insects are present. This is further complicated by differences in the numbers and amplitudes of sounds produced by different individuals, and different species and stages of insects. Also, the greater the distance at which insects can be detected the greater the possibility of picking up background sounds. Background sound can be reduced by sound proofing, using electronic filters or counting only sounds producing voltages above a certain level. Vick et al. (1988) evaluated and provided construction plans for a inexpensive sound-insulated room. When sensors are inserted into grain, the grain provides reasonably good sound proofing.

<u>Insect density</u> - A strong correlation between the number of insects and the number of insect sounds is the key to using an acoustical detection method. Calibration curves have been developed for rice weevil, lesser grain borer and Angoumois grain moth larvae on wheat, corn and rice (Vick et al. 1988, Hagstrum et al. 1988b), lesser grain borer adults on wheat (Hagstrum et al. 1990) and red flour beetle adults on wheat (Hagstrum unpublished). All of these studies showed a strong correlation between the number of sounds and the number of insects. Fleurat-Lessard & Andrieu (1986) detected insect densities as low as 5 granary or rice weevil larvae or 1 adult per kg of grain. Vick et al. (1988) were able to detect lower densities of one mature rice weevil larvae in 0.77 kg of wheat. In recent studies, Hagstrum (unpublished) detected even lower densities of two adult red flour beetles per 27.2 kg of wheat by frequently monitoring over a 24 h period 16 piezoelectric sensors inserted into 136 kg of wheat. These studies provide some of the information essential to the development of acoustical detection as a routine method for monitoring stored-grain insect infestations.

<u>Temporal variation in insect activity</u> - With acoustical sensors, detection depends upon insect activity. Both the sounds from larvae feeding on the grain and those from locomotor activity of larvae and adults moving around in the grain are detected. Vick et al. (1988) showed that, in grain samples, lesser grain borer, rice weevil and Angoumois grain moth larvae spent 61 to 90% of their time feeding and thus producing sounds. Red flour beetle larvae and adults are active 71 and 92% of the time, respectively (Hagstrum unpublished). This extensive

activity means that sensors monitored over time will detect insects from a large volume of grain because insects that are initially too far from a sensor to be detected will eventually move close enough to a sensor to be detected. In fact, studies by Hagstrum (unpublished), which monitor at 13 minute intervals 16 sensors in 136 kg of wheat, showed that each additional time sensors were monitored the probability of detection was improved by 60 to 80% as much as using an additional sensor.

Insect species and stage - Insect activity and thus the number of sounds detected varies with species and stage or instar of insects. Shade et al. (1990) found that the number of feeding sounds produced by the cowpea weevil increased with larval instar. Rice weevil, angoumois grain moth and lesser grain borer larvae were detected from 13, 16 and 19 days after oviposition until pupation (Vick et al. 1988). The number of sounds detected with rice weevil and Angoumois grain moth larvae averaged 3.57 and 1.15 times those detected with lesser grain borer larvae. Lesser grain borer adults (Hagstrum et al. 1990) and red flour beetle adults (Hagstrum unpublished) produced 37 and 80 times more sounds than larvae of the same species. The number of sounds detected from one adult red flour beetle, one adult rice weevil, 5 adult sawtoothed grain beetles, Oryzaephilus surinamensis (L.), and 5 adult rusty grain beetles, Cryptolestes ferrugineus (Stephens), averaged 460, 400, 13 and 6% of those detected from one adult lesser grain borer (Hagstrum unpublished). The relative number of insect sounds produced by various species and stages are compared in Table 1.

Table 1. Relative numbers of insect sounds

Stage & Species	Number of sounds
Adult red flour beetle	= 4.6
Adult rice weevil	= 4.0
Adult lesser grain borer	= 1.0
Larval rice weevil	= 0.096
Larval red flour beetle	= 0.057
Larval Angoumois grain moth	= 0.031
Larval lesser grain borer	= 0.027
Adult sawtoothed grain beetle	= 0.026
Adult rusty grain beetle	= 0.012

One approach to discriminating between species and stages of insects would be to determine the number of voltage spikes from sensors that were above two different voltage thresholds. Large insects, such as adult red flour beetles and adult rice weevils, produce large numbers of detectable sounds and more sounds which result in large voltage spikes from piezoelectric sensors. Small insects, such adult rusty grain beetles and insect larvae, produce few sounds which result in voltage spikes that large. If voltage spikes were above the highest then the species or stage present is one of those producing large voltage spikes. If voltage spikes were above lowest threshold, but not above the highest threshold then the species or stage present is probably one of those producing mostly small voltage spikes. However, the species producing mostly small voltage spikes can only be recognized using this method if those producing large voltage spikes are not present. Fortunately, the insect pests causing the most damage to stored grain tend to produce largest voltage spikes. This means that the numbers and amplitudes of sounds provides information about which species is present, but more information will generally be necessary to identify species. Because species vary in their distribution in the bin and population growth rates, this information also may help to identify insect species when populations are monitored over time. However, the most definitive method will be to take grain samples at the location at which insects are detected with acoustical sensors. Knowing when and where to take samples will greatly reduce the number of grain samples that need to be taken. Instead of taking grain samples from all bins throughout the storage period as is necessary with conventional grain sampling, with acoustical detection, grain samples will probably need to be taken only once to identify species and only from those bins which may need insect control.

Temperature - Temperature can also affect the level of insect activity and thus the number of insect sounds produced. Shade et al. (1990) showed that feeding activity of cowpea weevil larvae increased between 15 and 25°C, leveled off between 25 and 40°C, and then decreased between 40 and 46°C. Between 22 and 32°C, a temperature range common during much of the grain storage period (Hagstrum 1987), the level of lesser grain borer activity was apparently the same (Hagstrum et al. 1988b). At least for these species, this means that density estimates should not need to be adjusted for differences in insect activity over a fairly broad range of temperatures.

Type of grain - Sound spectra for the rice weevil, the lesser grain borer or the Angoumois grain moth larvae were similar on wheat, rice and corn, but peak frequencies varied between grains (Vick et al. 1988). The peak frequencies were 1200, 1475 and 587 Hz for wheat, rice and corn. Also, the number of sounds detected on corn and rice averaged 33 and 128% of those on wheat. This means that different calibration curves will be needed for each grain.

Sampling problem - To effectively manage stored grain, we may need to anticipate when insect control will be needed. With current sampling methods, insect infestations generally reach densities of 50 insects per 27.2 kg of grain before they are detected. Because insect population growth rates generally exceed 10-fold per month, the manager needs to detect insect densities of 5 insects per 27.2 kg of grain to know a month ahead when insect control measures would be needed. Another problem is that many samples are often necessary to accurately estimate insect population density, because insects are not uniformly distributed in grain (Hagstrum et al. 1985, Hagstrum et al. 1988a). Their studies convincingly showed the need for automation of insect detection. They indicate that over 100 samples per 27,200 kg of grain (1000 bushels) are required to be 95% confident of detecting insect densities of 5 insects per 27.2 kg of grain or estimating this density within ± 1 insect. Such large sampling efforts are not practical with conventional grain sampling methods, but are quite practical with the acoustical detection method. With conventional sampling methods, each grain sample must be sieved and the sievings must be examined for insects. This is a time-consuming task and does not detect immature insects feeding inside kernels. When no insects are found in samples, this only means that insect densities are below those detectable with the number of samples taken. Labor costs are further increased by the need for frequent sampling. Because insect populations can grow rapidly, it is necessary to resample frequently to be sure populations have not increased to unacceptable levels. Therefore, monitoring of insect populations can be the most costly part of pest management. Acoustical sensors can provide, without taking grain samples, density estimates of growing lesser grain borer populations that are comparable to estimates made by counting the number of adults in grain samples. This reduces cost and increases reliability.

Applications - Applications of the acoustical detection method include a desktop unit for determining the number of insects in grain samples, a portable probe for estimating the insect populations in stored grain without taking grain samples and permanently installed cables for monitoring insect populations in many bins at a grain storage facility from a single computer.

The desktop unit can be automated to process samples from the diverter type sampler as grain samples arrive in the laboratory for grading. A flow-through unit is currently being tested which has eight piezoelectric sensors evenly spaced in a 1 kg grain sample container and uses the software developed by Webb et al. (1988) to record with a personel computer the number of insect sounds detected. With this software it takes less than two minutes to process a sample. It should be possible to modify the computer software to start counting the number of insect sounds when a new sample arrives, to release the sample after recording the number of insect sounds, and to interpret the number of insect sounds in terms of the number of insects present in the sample. Thus, many samples could be processed automatically improving the reliability of insect monitoring.

A second approach is the portable probe used by Hagstrum et al. (1988b). This system was composed of a durable piezoelectric microphone mounted on the end of a probe which was pushed into the grain, a battery operated amplifier and earphones for listening to insect produced sounds. Although earphones were used in these studies to detect insect sounds, a portable microprocesser should be used to collect and analyze data as we did with the desktop unit, if this approach is to be used commercially. The portable probe allows insect infestations to be located and their densities to be estimated without taking grain samples. This should be particularly useful to contract fumigators in determining whether a bin needs to be fumigated and whether fumigation has been effective or to elevator managers in determining before it is unloaded whether a truck or barge load of grain is infested.

Permanently mounted cables in grain storage bins can be used to automatically, remotely, and continuously monitor insect populations. If all of the bins at a large elevator were equipped with acoustical sensors, the computer monitoring the facility could provide a list of the bins that may need insect control within the next month. The expert system developed by Flinn & Hagstrum (1990) could provide in the same list information on when insect control would be needed and the type of insect control that should be used for each bin. A computer network keeping track of the movement of grain through the marketing system could recommend optimal management for each lot of grain regardless of where it is in the marketing system. This network would also be a powerful research tool for improving methods of managing insect pests.

Conclusion

Acoustical sensors which automatically alert us to the need for insect control can improve pest management by reducing the chances of an infestation going undetected. The strong correlation between insect density and the number of sounds detected is the key to using acoustical sensors to monitor insect populations. Information on differences between species and stages of insects in the numbers of sounds produced and detection distances, and temporal variation in insect activity should allow us to more precisely estimate population densities. Perhaps the main limitation of acoustical detection is the inability to definitively indicate which insect species are present. However, acoustical detection will minimize the number of grain samples needed to determine which species are present by telling us when and where to take grain samples.

References

Adams, R. E., J. E. Wolfe, M. Milner & J. A. Shellenberger. 1953. Aural detection of grain infested internally with insects. Science 118: 163-164.

Bailey, S. W. & J. B. McCabe. 1965. The detection of immature stages of insects within grains of wheat. J. Stored Prod. Res. 1: 201-202.

Bruce, W. A., M. W. Street, R. C. Semper & D. Fulk. 1982. Detection of hidden insect infestations in wheat by infrared carbon dioxide gas analysis. Advances in Agric. Tech., South. Series, No. 26, U.S. Dept. Agric., pp. 1-8.

Chambers, J., N. J. McKevitt & M. R. Stubbs. 1984. Nuclear magnetic resonance spectroscopy for studying the development and detection of the grain weevil, Sitophilus granarius (L.) (Coleoptera: Curculionidae), within wheat kernels. Bull. Entomol. Res. 74: 707-724.

Fleurat-Lessard, F. & A. J. Andrieu. 1986. Development of a rapid method to determine insect infestation in grain bins with electro-acoustic devices. Proc. 4th Intern. Working Conf. Stored Product Protection, Tel Aviv, Israel. p. 643.

Flinn, P. W. and D. W. Hagstrum. 1990. Stored Grain Advisor: a knowledge-based system for management of insect pests of stored grain. AI Applications in Natural Resource Management. (in press).

Hagstrum, D. W. 1987. Seasonal variation of stored wheat environment and insect populations. Environ. Entomol. 16: 77-83.

Hagstrum, D. W., R. L. Meagher & L. B. Smith. 1988a. Sampling statistics and detection or estimation of diverse populations of stored-product insects. Environ. Entomol. 17: 377-380.

Hagstrum, D. W., G. A. Milliken & M. S. Waddell. 1985. Insect distribution in bulk-stored wheat in relation to detection or estimation of abundance. Environ. Entomol. 14: 655-661.

Hagstrum, D. W., K. W. Vick & J. C. Webb. 1990. Acoustical monitoring of Rhyzopertha dominica (F.) (Coleoptera: Bostrichidae) populations in stored wheat. J. Econ. Entomol. 83: 625-628.

Hagstrum, D. W., J. C. Webb & K. W. Vick. 1988b. Acoustical detection and estimation of Rhyzopertha dominica larval populations in stored wheat. Florida Entomol. 71: 441-447.

Milner, M., M. R. Lee & R. Katz. 1950. Application of x-ray technique to the detection of internal insect infestation of grain. J. Econ. Entomol. 43: 933-935.

Shade, R. E., E. S. Furgason & L. L. Murdock. 1990. Detection of hidden insect infestations by feeding-generated ultrasonic signals. Amer. Entomol. 36: 231-234.

Street, W. M., Jr. 1971. A method for aural monitoring of in-kernel insect activity. J. Ga. Entomol. Soc. 6: 72-75.

Vick, K. W., J. C. Webb, D. W. Hagstrum & C. A. Litzkow. 1990. Modification of the grain probe trap for remote determination of the number of stored-product insects. J. Econ. Entomol. (in press).

Vick, K. W., J. C. Webb, D. W. Hagstrum, B. A. Weaver & C. A. Litzkow. 1988. A sound-insulated room suitable for use with an acoustic insect detection system and design parameters for a grain sample holding container. Fla. Entomol. 71: 478-484.

Vick, K. W., J. C. Webb, B. A. Weaver & C. Litzkow. 1988 Sound detection of stored-product insects that feed inside kernels of grain. J. Econ. Entomol. 81: 1489-1493.

Webb, J. C., C. A. Litzkow & D. C. Slaughter. 1988. Computerized acoustical larval detection system. Appl. Eng. Agric. 4: 268-274.

LA DETECTION ACOUSTIQUE AUTOMATIQUE DES RAVAGEURS DU GRAIN : UN MOYEN DE REDUIRE LES PROBLEMES POSES PAR LES INSECTES.

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RESUME

Les détecteurs acoustiques qui nous alertent automatiquement lorsque la nécessité de lutter contre les insectes devient urgente peuvent améliorer la gestion de la protection du stock en réduisant les risques de ne pas détecter une infestation. De même, la surveillance des ravageurs du grain peut représenter la fraction la plus lourde de budget de cette gestion. La détection acoustique peut fournir un moyen, fonctionnant en continu et automatique pour surveiller les populations d'insectes, à faible coût. Comparée aux autres méthodes, la capacité d'exercer une surveillance automatique est un avantage certain. Les détecteurs acoustiques peuvent fournir des estimations sur la densité des populations de larves du petit capucin des grains, comparables à celles obtenues par la méthode de comptage des adultes dans des échantillons, sans avoir à en prélever. Le "coeur" de la méthode acoustique réside dans la bonne estimation du rapport existant entre le nombre de bruits qu'ils émettent. Ces études fournissent certaines des informations essentielles nécessaires au développement de la détection acoustique en tant que méthode de routine de détection des infestations de ravageurs de grain. Les applications de cette méthode comprennent une unité de mesure du nombre d'insectes dans des échantillons de grain, une sonde permettant la mesure des populations des stocks sans avoir à prendre d'échantillons, ainsi que des câbles installés en permanence et servant à la surveillance des populations des diverses cellules d'un magasin de stockage à partir d'un seul poste.