RESEARCH

Perspective and Promise: a Century of Insect Acoustic Detection and Monitoring

R. W. Mankin, D. W. Hagstrum, M. T. Smith, A. L. Roda, and M. T. K. Kairo

Abstract: Acoustic devices provide nondestructive, remote, automated detection, and monitoring of hidden insect infestations for pest managers, regulators, and researchers. In recent decades, acoustic devices of various kinds have been marketed for field use, and instrumented sample containers in sound-insulated chambers have been developed for commodity inspection. The efficacy of acoustic devices in detecting cryptic insects, estimating population density, and mapping distributions depends on many factors, including the sensor type and frequency range, the substrate structure, the interface between sensor and substrate, the assessment duration, the size and behavior of the insect, and the distance between the insects and the sensors. Considerable success has been achieved in detecting grain and wood insect pests. Microphones are useful sensors for airborne signals, but vibration sensors interface better with signals produced in solid substrates, such as soil, grain, or fibrous plant structures. Ultrasonic sensors are particularly effective for detecting wood-boring pests because background noise is negligible at > 20 kHz frequencies, and ultrasonic signals attenuate much less rapidly in wood than in air, grain, or soil. Problems in distinguishing sounds produced by target species from other sounds have hindered usage of acoustic devices, but new devices and signal processing methods have greatly increased the reliability of detection. One new method considers spectral and temporal pattern features that prominently appear in insect sounds but not in background noise, and vice versa. As reliability and ease of use increase and costs decrease, acoustic devices have considerable future promise as cryptic insect detection and monitoring tools.

Long ago, insect predators and parasitoids began eavesdropping on communication sounds (Cade 1975, Zuk and Kolluru 1998) as well as feeding and movement sounds and vibrations (Meyhöfer and Casas 1999) to find prey and hosts. Humans were latecomers to eavesdropping, but soon after it became possible to record and produce sound electronically, they began developing potential applications for detection of insect presence or bsence, and for monitoring of activity over time. A journal article on acoustic detection of termites was published in 1909 (Main 1909). Other early popular reports included those on stored-product weevils (Anon. 1935) and termites (Escherich 1911; Snyder 1935, 1952). Since then, at least 132 additional articles or patents have been published on acoustic or vibrational detection and monitoring of insects, mostly within the last 20 years (Table 1). Sound and vibration measurements have been discussed in numerous reviews of insect detection and monitoring (Thorne 1993, Rajendran 1999, Reynolds and Riley 2002, Hagstrum and Subramanyam 2006, Johnson et al. 2007).

Adults of the many insect species that use sounds or vibrations in communication are prominent candidates for acoustic detection and monitoring studies. Hill (2008) identified 218 such species in 12 insect orders. Considering the diversity of signals referenced in papers by Rudinsky and Michael (1973), Spangler (1988), Stewart (1997), Virant-Doberlet and Čokl (2004), Cocroft and Rodriguez (2005), and Wessel (2006), the total number may be much larger. Many of these signals are optimized for detection over long distances (Forrest 1988), including cicada and cricket calling songs, and they typically contain important information about the species and sex of the sender. Mankin (1994) monitored wing beat sounds to detect swarms of *Ochlerotatus taeniorhynchus* (Wiedemann) salt marsh mosquitoes, and Lampson et al. (2010) characterized the frequency and temporal patterns of communication vibrations produced by different species of hemipterans to detect them in cotton fields. Birch

Table 1. Publications on insect acoustic detection and monitoring per decade

Decade	No. Publications
1901-1910	1
1911-1920	1
1921-1930	2
1931-1940	4
1941-1950	0
1951-1960	5
1961-1970	4
1971-1980	4
1981-1990	22
1991-2000	44
2001-2010	50
Total	137

and Menendez (1991) suggested that the female deathwatch beetle, *Xestobium rufovillosum* (DeGeer), could be detected by vibrating infested timbers with amplified communication taps of calling males, which would elicit responsive taps from the female that are loud enough to be heard by the human ear. Forrest (1988) proposed the use of communication sounds to estimate orthopteran populations in the field. Insect communication sounds also have been used to lure insects into traps (Walker 1988).

Apart from insects that produce communication signals, many economically important coleopteran adults and larvae and lepidopteran larvae with cryptic behaviors also are candidates for acoustical and vibrational detection and monitoring, especially those that are large and active, sometimes even producing sounds audible to humans, like the red palm weevil, *Rhynchophorus ferrugineus* (Olivier) and the coconut rhinoceros beetle, *Oryctes rhinoceros* (L.). The incidental signals that small cryptic insects produce while moving and feeding can be very low in amplitude but still detectable. Movement and feeding sounds of 4th instar *Sitophilus oryzae* (L.) in grain are only 23 dB (Mankin et al. 1996), for example, where dB is calculated as $20 \log_{10}(P/P_{ref})$, P is the sound pressure and $P_{ref} = 20$ µPa is the threshold of human hearing. Typical noise levels in a quiet, 35–50 dB office are ~4 times (12–27 dB) higher. Acoustic devices with optimized filters and sensors have detected *S. oryzae* larvae in many different environments, however, as is discussed below.

As the use of acoustic technology for entomological applications began expanding in the 1980s and 1990s, Walker (1996) noted that acoustic methods seemed destined to rapidly replace many of the labor-intensive and less effective detection and monitoring methods then in use. However, while our understanding of insect acoustical and vibrational communication has blossomed in the last decade (Cocroft and Rodriguez 2005, Drosopoulos and Claridge 2006, Čokl 2008, Sueur et al. 2008, Barbero et al. 2009), the development and adoption of inexpensive, user-friendly acoustic tools for detection and monitoring of economically important infestations of hidden insects has lagged behind. The delays have resulted partly from limited understanding of acoustic signal attenuation in and across various substrates; from difficulties of interpreting weak insect signals in environments with high background noise; from limited knowledge of the behaviors of the cryptic targeted species that produce the signals; and from the small market for insect detection instrumentation, which limits the capability to take advantage of economies of scale. For example, notably fewer insect acoustic detection devices than electronic stethoscopes are sold yearly. Electronic stethoscopes have been used successfully for insect detection (e.g., Kisternaya and Kozlov 2009), but there are many insect detection applications where more optimal sensor-substrate interfacing or higher-gain amplification is required, as is discussed in later sections.

To avoid confusion about acoustics terminology, we note here that several terms used in this report, including "sound," "vibration," "signal," "acoustic," and "remote," have taken on multiple meanings in the biological, acoustical, and signal processing literature. The term "signal" will be used primarily in two contexts: either physically as a sound in air or a vibration in a structure, and also mathematically as an amplitude-time waveform. Both sound and vibration waveforms are processed by similar "acoustic" signal processing methods. Frequently, insect-produced signals are detectable both by microphone as sounds and by contact sensors as vibrations, in which case they may be designated simply as "acoustic signals" or "sounds" (Webb et al. 1988a). We have avoided using "signal" in the biological sense of transmitting information between or among individuals or groups of organisms. Finally, acoustic detection or monitoring is "remote" in the sense that it typically occurs over distances of tens of centimeters or more, depending on the substrate in which the insect is hidden (Reynolds and Riley 2002). In many applications, wires or wireless devices transmit the signals from the hidden insect to a central observation station that can be hundreds of meters distant.

In this report, we describe the progress made during the last century in the development of acoustic tools and applications for cryptic insect detection, population estimation, and distribution mapping. The report is organized into nine sections, the first five of which deal with how acoustic signals are transmitted, sensed, and interpreted in different environments. Three sections deal with applications of acoustic methods in detection, population estimation, and mapping of cryptic insects in different environments. In the final section, we consider the kinds of applications toward which acoustic technology may be directed in the future.

Transmission and Attenuation of Insect Acoustic Signals in and between Stored Products, Wood, and Other Substrates

Acoustic attenuation (the gradual loss of magnitude as an acoustic signal passes through a substrate) is the result of absorption within the substrate, reflections at interfaces, and dilution as the signal enters a larger volume. It can severely limit the distance over which sensors can detect insects reliably (the active space), and it can strongly degrade signals that move across substrate interfaces; for example, from grain to air, or from a weathered palm frond to a stethoscope head.

In heterogeneous substrates like wood or storage bins of grain or beans, reflection plays a strong role in attenuation, with sound moving a short distance in transfers or reflections from grain to grain, bean to bean, or across wood fibers, while it can move longer distances through air spaces (Guo et al. 2005, Hickling and Wei 1995, Hickling et al. 1997a) or along a wood fiber. The attenuation coefficient, or rate of signal decay per unit distance, is ca. 2–5 times greater across wood or plant fibers than along them (Robbins et al. 1991, Scheffrahn et al. 1993). Termites can be detected 0.8 to 2.2 m from the sensor location along the wood grain, (Lemaster et al. 1997, Yanase et al. 2000) but only ca. 8 cm away across the wood grain (Scheffrahn et al. 1993).

The attenuation coefficient increases 1,000-fold between 500 Hz and 120 KHz in air (Mankin et al. 1996), and at even greater rates in soil and grain (Mankin et al. 2000), making both substrates highly effective insulators against high-frequency sound. Wood has a low attenuation coefficient; consequently, ultrasound (i. e., frequencies > 20 kHz) could be detected from termites over active spaces of up to 2.2 m in wood (Scheffrahn et al. 1993). Low-frequency sounds from termites and other insects can be detected over active spaces of 180 cm, but only over 20 cm in soil (Mankin et al. 2002). Low-frequency sounds produced by infestations of red palm weevil larvae in the crown of a palm tree can be detected easily by sensors positioned 2 m below the crown, and some of the loudest sounds are detectable from 4 m and further below. Because of the significantly lower rate of attenuation at lower frequencies, listeners often focus on low-frequency signals to increase the active space.

Attenuation and resonances within a substrate alter the spectrum of an insect sound as it passes through a tree, grain, or soil (Vick 1988b, Mankin et al. 2008a, b). Consequently, the mean spectrum of signals produced by a targeted species is different in different substrates, and it changes with distance from insect position. In addition, many sensors are differentially sensitive to different sound frequencies. All these differences must be taken into account when signals and spectra recorded from different sensors in different environments are compared.

Sound and Vibration Sensors

Some of the first sensors used for acoustic insect detection (Lutz 1924, Emerson and Simpson 1929) were carbon button microphones (Dyer 1997), denoted by (m) in the tables below, replaced later by dynamic condenser or capacitive microphones (m_c) after the introduction of vacuum tube amplifiers. Electret microphones (m_e), a special class of inexpensive capacitive microphones, came into common use after the 1960s (Sessler and West 1962), but condenser microphones (m_c) are still used where high quality and good calibration are needed. Modern microphone systems are capable of 60–120 dB gain (10^3–10^6 amplification) with nearly constant response over ~0–20 kHz frequency range.

Microphones are useful sensors for airborne signals, but they do not interface well with signals produced by insects in soil, wood, or other solid substrates. Sensors that interface better with solid substrates include piezoelectric transducers (Gautschi 2002) that function as contact microphones or pickups (p), geophones (g), accelerometers (p_a), or ultrasonic sensors (p_u). Magnetic cartridges were used as inexpensive pickups before piezoelectric transducers became popular, and are still used occasionally. Accelerometers and some geophones measure acceleration, while other geophones measure the velocity of substrate vibrations. Geophones detect low-amplitude, low-frequency signals, ~0–400 Hz, and the most commonly used accelerometers operate up to frequencies of ~13 kHz. Ultrasonic sensors operate at frequencies between 20 to 200 kHz and higher (Haack et al. 1988). Accelerometers are more expensive, but usually better calibrated and more rugged than contact microphones. It is important to note, however, that the choice of sensor depends significantly on the purpose of its use. Farr and Chesmore (2007) found, for example, that piezoelectric sensors were preferable to electret microphones when the primary goal was detection of wood-boring insects because the piezoelectric sensors have greater sensitivity, but due to their greater spectral range, electret microphones were better at distinguishing between insect sounds and background noise.

Ultrasonic sensors are of particular utility for detection and monitoring of wood-boring insects. Termites (Fujii et al. 1990) and other wood-boring insects stress and snap wood fibers during movement and feeding activities, which causes the wood fibers to spontaneously emit broad-band acoustic emissions (first characterized by Dornfeld and Kannatey-Asibu 1980) that can be detected by lead-zirconate-titanate (PZT) ceramic-disk (Gautschi 2002) and polyvinylidene fluoride (PVDF) film (Yanase et al. 1998) piezoelectric transducers. Lemaster et al. (1997) determined that the detectability of acoustic emissions from termite infestations depended on the resonant frequencies of the piezoelectric transducers, with transducers that had resonant frequencies near 60 kHz providing the best overall performance for ultrasonic signal detection. The cost and durability of ultrasonic and other piezoelectric transducers vary over a wide range, and large differences also exist in the sensitivity and calibration of their amplifiers. Amplifiers with 40–100 dB gain are sufficient for detection of most insect sounds, but greater amplification can be provided by various methods if needed; e.g., fluidics methods (Drzewiecki and Shuman 2001).

The sensor-substrate interface can strongly affect the sensitivity and reliability of vibration measurements. The ideal mounting for an accelerometer is to use a nail, screw, or other metal waveguide inserted into the substrate. If the waveguide is magnetic, it can be inserted into the substrate first, and then connected magnetically to the accelerometer (Mankin et al. 2000). Sensors also can be attached with glue, beeswax, or solid adhesives like Ross Tac ' N Stick (Elmer's Products Corp., Columbus, OH), although loose-fitting connections may have low sensitivity at high frequencies. Rapid surveys can be conducted with hand-held probes or stethoscope heads, but magnitude measurements are not repeatable in such cases, especially when the sensor is placed against a rough surface. Sensitivity is reduced when insects strongly compromise the structural integrity of the substrate; for example, when a heavy infestation of red palm weevil larvae destroys significant portions of the interior of a palm tree trunk.

In cases where insect signals in a solid substrate have a narrow frequency range, it may be feasible to combine a microphone with a resonant acoustic coupler (Webb et al. 1988a) to achieve even greater sensitivity than a contact sensor would provide. Aural and electronic stethoscopes operate similarly to acoustic couplers and have been useful for insect detection when the base of the stethoscope can be placed flush with the substrate surface (Kisternaya and Kozlov 2009). Stethoscopes and acoustic couplers do not work as well in contact with rough surfaces, however, or when the insect sounds cover a broad frequency range. Other sensor combinations have also been used in different insect acoustic detection applications, including expensive but highly precise laser vibrometers (Michelsen and Larsen 1978, Žunič et al. 2008) and inexpensive magneto-inductive sensors (e.g., Strübing 2006).

Minimizing Electrical and Background Noise

Electrical and background noise can be mistaken for insect sounds, and considerable research has been conducted to minimize or filter out interfering signals. Most of the electrical noise problems in field environments are interconnection problems, which can be reduced by placing the amplifier and the analog-to-digital converter as close to the sensor as possible. When many sensors are used, having one amplifier for many sensors is less costly. Shielding the cables connecting sensors to the amplifier, eliminating ground loops, and separating power cables from input/output cables also reduce electrical noise (Macatee, 1995).

When feasible, acoustically and vibrationally shielded anechoic chambers (Pittendrigh et al. 1997, Vick et al. 1988, Webb et al. 1988a, b) or other sound-proofing and vibration reduction methods are commonly employed to reduce background noise (Adams et al. 1954, Fleurat-Lessard 1988, Vick et al. 1988a; Hagstrum and Flinn 1993, Hickling et al. 1994, 2000; Mankin et al. 1996, 1997b). Generally, a box-within-a-box construction and sound-absorbent material are used for sound-proofing. Vibration is reduced by suspending the sample container, and by using heavy supporting materials and shock mounts. Electrical noise interference in an industrial environment can be reduced by enclosing the chamber within a copper Faraday cage (Adams et al. 1954).

Another commonly used procedure to reduce background noise is to include reference sensors into the instrumentation to identify periods of background sounds or electrical noise (Scheffrahn et al. 1993, Pittendrigh et al. 1997, Hagstrum et al. 1996). Reference sensors also have been used to subtract out signals that appear simultaneously in the test sensors and the external background (Mankin et al. 2010 and references therein). If enough of the background noise can be shielded, it is possible to use a very simple signal processing system that counts sounds as the number of times the voltage rises above a predetermined threshold level (Webb et al. 1988a).

Filtering out frequencies higher or lower than those typically produced by the target species reduces background noise that cannot be eliminated by methods above. Much background noise, for example, is low-frequency and can be reduced significantly by filtering out signals below 200 Hz (Mankin et al. 2009b). Wind, machinery, and traffic are examples of such noise. Bird calls and nontarget flying insect sounds usually have strong harmonic components (Mankin et al 2009b, Potamitis et al. 2009) that typically do not appear in movement and feeding sounds of hidden insects. Examples of bird-call noise are seen in comparison with signals produced by an *Anoplophora chinensis* (Forster) larva in Fig. 1. The signals were digitally recorded (digitization rate, 44.1 kHz) from the root system of an *Acer pseudoplatanus* L. tree in the yard of a condominium complex near Como, Italy using a piezoelectric pickup. The signals were bandpass-filtered between 0.2 and 10 kHz, as in Mankin et al. (2008c), and individual sounds were identified aurally by playback and by digital signal analyses, as in Mankin et al. (2009b). The spectrogram, Sp, in Fig. 1 displays a diffuse band of background noise with a peak near 1.5 kHz. The blocked area, AC, contains numerous 3–30 ms, broad-band *A. chinensis* sound impulses that appear as brief spikes of varying amplitudes in the oscillogram and as lines that span most or all of the frequency range in the spectrogram. One of several loud mechanical impacts occurs at ~11 s, marked as blocked area N. The impact has a strong peak below 500 Hz and little energy above ~4 kHz. In contrast, several bird calls, the first one marked as block B, contain most of their energy in a series of harmonics above 4 kHz. The dashed ovals in N and B mark frequencies where the relative energy is notably different from that in larval signals.

Use of Signal Features to Discriminate Target from Nontarget Species and Other Noise

Although background noise can be reduced substantially, it is rarely eliminated, and identifying and distinguishing low-amplitude target insect signals from other sounds sometimes can seem an impossible challenge. The human ear deals with such challenges routinely, however, and recognition of the methods used by human and other animal auditory systems to identify weak signals of interest has led to considerable progress in development of automated insect acoustic detection and monitoring methods. Recently developed methods include recognition of spectral and temporal features that prominently appear in target insect signals, but not otherwise or vice versa, and recognition of how spectral features are affected by the substrate, as seen in Figs. 1–2. The block (AC) of signals from the *A. chinensis* larva in Fig. 1 and the entire oscillogram (Os) in Fig. 2 both display a series of short, broadband, variable-amplitude impulses (transients) that are typical of larval sliding and scraping, wood-fiber snapping, and other movement and feeding activity (Mankin et al. 2008c). The signals in Fig. 2 were obtained from a large infestation of red palm weevil larvae found in the crown of a 5 m date palm in Curaçao. In both cases, the sounds are a combined result of insect action with the wood-fiber reaction.

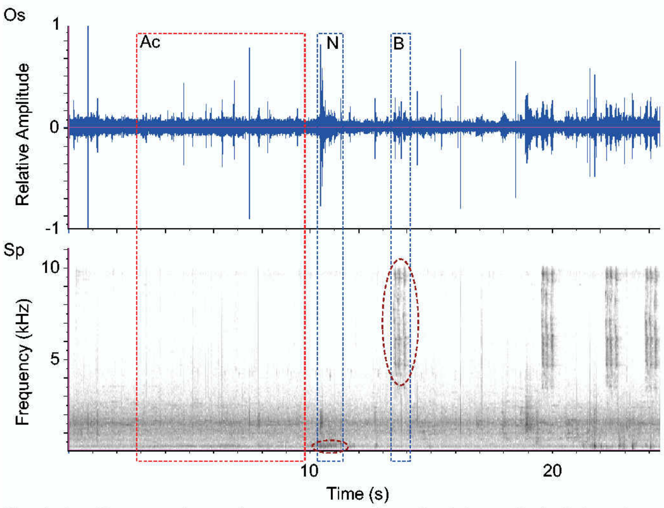

Fig. 1. Oscillogram, Os, and spectrogram, Sp, of a 24 s period of signals recorded from a tree containing an *A. chinensis* larva. Darker shading in spectrogram (512 points per spectrum, 90% overlap) indicates higher relative spectrum level (higher energy). Blocked area, AC, marks a period with numerous *A. chinensis* impulses; N marks a period of mechanical noise; and B marks a bird call. Ovals in N and B mark frequency ranges where relative spectrum levels notably exceed those expected in larval signals.

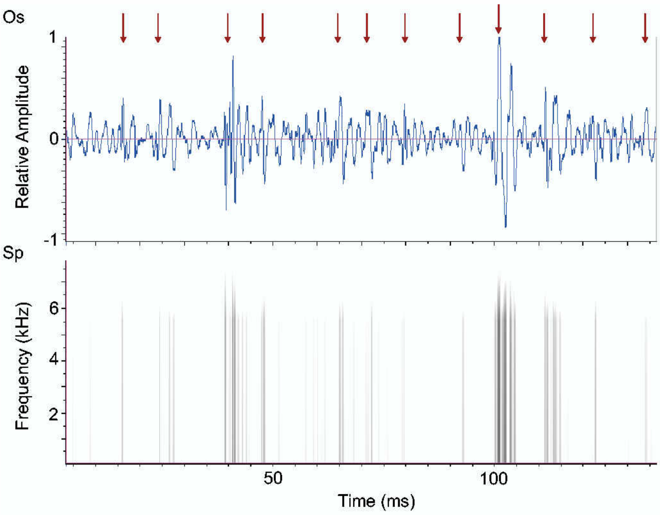

Fig. 2. Oscillogram, Os, and Spectrogram, Sp, of a 0.13 s period of impulses recorded from a palm containing multiple *R. ferrugineus* larvae. Darker shading in spectrogram (8 points per spectrum, 90% overlap) indicates higher relative spectrum level. Individual impulses are marked by arrows. Recording and analysis methods were essentially as described in Mankin and Moore (2010).

The effect of the wood fibers on the spectra of insect sounds is clearly discernable in Fig. 3, where the average spectral pattern (profile) of 240 consecutive *R. ferrugineus* impulses recorded from the crown is seen in line Rf of Fig. 3. This is compared with the mean spectrum of 0.5 s of background noise (Rfb) recorded from the same position. Also included in Fig. 3 is a profile (Ac) of 24 signals produced by an *A. chinensis* larva in the tree where Fig. 1 was recorded, compared with the mean spectrum of 0.5 s of background noise recorded from the same position. The Rf and Ac profiles have a similar overall shape, but their peaks are shifted, corresponding with shifts in the peaks of the background noise (Rfb and Acb). The shifts in the peaks of the background noise occurred because of resonances within the tree structure that depend on the length, diameter, and stiffness of the trunk (Mankin et al. 2008c). In both cases, the larvae produced signals that had greater energy than the background at frequencies above the peak frequency of the background noise.

The profile Rf in Fig. 3 is similar to other *R. ferrugineus* profiles in Mankin et al. (2008b) recorded from a small potted palm tree and from sugarcane. The primary difference is that the resonant

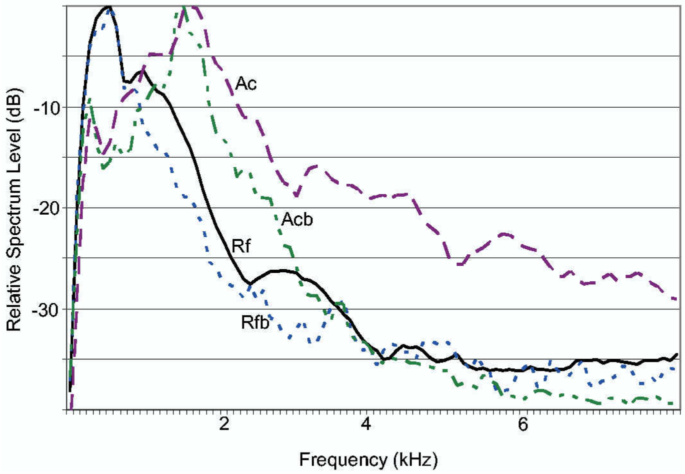

Fig. 3. Spectra of *R. ferrugineus* profile recorded in crown of date palm, Rf; background noise in same date palm, Rfb; *A. chinensis* profile recorded in *A. pseudoplatanus* tree, Ac; and background noise in same tree, Acb.

frequency of the palm tree trunk is much lower than the resonant frequency of the much smaller potted palm. Such effects of structure size on the resonances observed when recording larval movement and feeding activities are observed most commonly in trees, but we also have observed resonance differences between signals produced in large and small containers of ornamental plants by black vine weevil, *Otiorhynchus sulcatus* (Fabricius) (Mankin and Fisher 2002).

In a given substrate, stored-product insect larvae can often be distinguished from adults through differences in movement and feeding activities that alter the spectral profiles of the sounds produced in a given substrate. An example is the discrimination of *Sitophilus granarius* (L.), *Tribolium confusum* Jacquelin du Val, and *Rhyzopertha dominica* (F.) larvae from each other in grain (Schwab and Degoul 2005). Because of their large size and distinctive acoustic profiles, red palm weevil larvae have been detected on the basis of spectral features alone with as high as 99% success in field trials (Potamitis et al. 2009). Gutiérrez et al. (2010) distinguished red palm weevil larvae from other insects in date palms on the basis of spectral features. Adults of different stored-product insect species can be distinguished by differences in their spectral profiles in a given environment. *Sitophilus granarius*, *T. confusum*, and *R. dominica* (F.) in grain were distinguished from each other in a study by Schwab and Degoul (2005).

Another distinctive feature of larval signals is their temporal pattern, which usually contains bursts or groups of impulses separated by intervals less than 250 ms (Mankin et al. 2008c, 2009b). In contrast, background noise often is continuous over periods of several seconds or occurs as isolated impulses rather than bursts. Human ears and automated detection systems are well suited to recognition of these differences in temporal patterns, which are the most reliable indicators of insect presence in environments with high levels of background noise. In trees, *Nasutitermes luzonicus* Oshima and adult *O. rhinoceros* were distinguished by a combination of spectral and temporal pattern analyses in a study by Mankin and Moore (2010). In soil, target species also have been distinguished from nontarget species and background noise by combinations of spectral and temporal pattern analyses (Mankin et al. 2009b).

Communication sounds of four different orthopteran insects were distinguished by Chesmore (2001) and Chesmore and Ohya (2004) using a feature extraction and classification procedure involving time domain signal coding and artificial neural networks. The accuracy of identification ranged from ~70 to 100%, depending on the calling song and the type of background noise in analyses with *Chorthippus albomarginatus* (De Geer), *Chorthippus parallelus* (Zetterstedt), *Myrmeleotettix maculatus* (Thunberg), *Omocestus viridulus* (L.), and several bird species. Hussein et al. (2010) considered time domain signal coding as well as 30 other temporal and spectral pattern features of red palm weevil sounds in distinguishing them from background noise. They achieved a 94% rate of success in distinguishing red palm weevil sounds from background

Effects of Insect Size and Stage, Disturbance Behavior, and Temperature on Acoustic Signal Production

Insect size and stage strongly affect the amplitude and rate of sound production. Sensors can detect *S. oryzae* larvae up to 10–15 cm away in grain (Vick et al. 1988a) and *Tribolium castaneum* (Herbst) adults up to 18.5 cm away (Hagstrum et al. 1991), for example, but the rates of sounds detected from a small insect close to a sensor may be similar to those detected from a larger insect further away. Adult *R. dominica* moving on the outside of the grain kernels produced 37 times more sounds than larvae feeding inside the grain (Hagstrum et al. 1990), and *T. castaneum* adults produced 80 times more sounds than larvae (Hagstrum et al. 1991). The rate of sounds produced by S. oryzae larvae in grain (Pittendrigh et al. 1997, Hickling et al. 2000) and *Callosobruchus maculatus* (F.) larvae in cowpeas, *Vigna unguiculata* (L.) Walp., (Shade et al. 1990) increased with instar. Adult *S. oryzae* and *T. castaneum* are equally detectable in grain and much more readily detected than smaller *Cryptolestes ferrugineus* (Stephens) or *Oryzaephilus surinamensis L.*, while the size and detectability of *R. dominica* are intermediate (Hagstrum and Flinn 1993). However, the data collected by acoustic sensors from grain infested with a single species and stage typically provides sampling statistics similar to those estimated from grain samples for *R. dominica* larvae (Hagstrum et al. 1988) and *T. castaneum* adults (Hagstrum et al. 1991). In both of these studies, the rates of insect sounds were highly correlated with the numbers of insects present. In other studies where multiple species and stages of root-feeding insects were present at sampling sites, the relationship between sound rate and the numbers of insects was of relatively weak statistical significance (Mankin et al. 2001, Mankin and Lapointe 2003, Zhang et al. 2003b).

Some insects flee and others feign death when disturbed (e.g., Miyatake et al. 2008), resulting in either positive or negative effects on sound production. Disturbance of fourth-instar *S. oryzae* by stirring grain may reduce sound production for periods up to 20 min (Mankin et al. 1999). For termites, however, dropping a 6 g coin three times to simulate disturbance during termite inspection did not reduce detectability significantly (Scheffrahn et al. 1993), and Hu et al. (2003) demonstrated that the response of termite colonies to 120 and 240 Hz vibration habituates within about 250 s. In the absence of knowledge about specific effects of disturbance, a listener can perform preliminary testing to assess activity with headphones at a location where the targeted species is known to be present and determine whether activity rates increase with time.

Insect sound production increases as the temperature increases from 10 to 25–30°C for adults or immatures of six insect species (Fig. 4), probably as a result of increases in insect feeding activity. *T. castaneum* adult sound production continued to increase up to 40°C. *Callosobruchus maculatus* larval sound production (Shade et al. 1990) decreased above 38°C in cowpeas. Sound production of *S.*

oryzae adults decreased above 30–35°C, and that of *R. dominica* adults began to level off above 30°C. For all species, including *Zootermopsis nevadensis* (Hagen), activity dropped off steeply as temperatures increased past optimal levels. *Incisitermes minor* (Hagen) was more active at 60 or 70% relative humidity than at 80 or 90% relative humidity (Indrayani et al. 2007). For insect communication among Orthoptera, the sound pulse rate was observed to increase as the temperature increased from 17 to 32°C (Sanborn 2006).

Several studies have investigated the effectiveness of warming insects to increase detectability. Warming grain from 11 or 17°C increased the sound production of *S. oryzae* larvae feeding inside by as much as 20- to 30-fold (Mankin et al. 1999). A patent was issued in France for heating grain to increase insect sound production (Mihaly 1973). Warming cotton bolls also increased sound production by pink bollworm larvae, *Pectinophora gossypiella* Saunders (Au 1997).

Effect of Assessment Time on Detectability

Because insects produce sounds of different amplitudes intermittently, increasing the duration of assessment can increase the likelihood that an insect inside the active space of a sensor will produce a detectable signal. Termites, for example, are detected with greater reliability using 5 min compared to 1 min monitoring periods (Scheffrahn 1993). The increased duration also increases the cost of assessment, which results in a trade-off between accuracy and cost.

Under conditions of low disturbance at temperatures that support activity of the target species, short 30–180 s listening times are suitable for many detection applications. The stored-product insects, *R. dominica*, for example, produce feeding sounds in grain 61% of the time, *Sitotroga cerealella* (Olivier) 71% of the time, and S. oryzae 90% of the time (Vick et al. 1988b), and sampling durations of 180 s usually will include at least one period of activity. Increasing the duration of monitoring of a sensor can be equivalent to increasing the number or size of grain samples. Increasing the frequency of monitoring of a sensor increased detection of T. castaneum by 60–80% as much as adding the same number of sensors (Hagstrum et al. 1991). In general, however, it is less costly to increase the sampling duration than the number of sensors. Stored grain beetle infestation levels

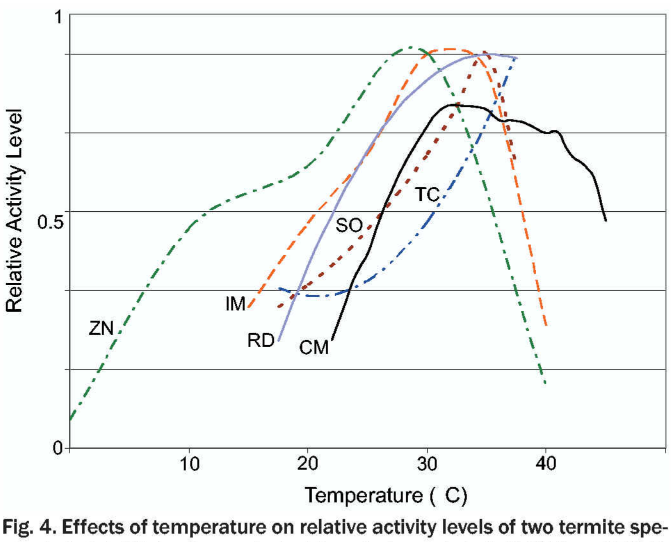

Fig. 4. Effects of temperature on relative activity levels of two termite species (adults): IM, I. minor, adapted from Indrayani et al. (2007); and ZN, *Z. nevadensis*, adapted from Lemaster et al. (1997); and four stored product insect species: CM (larvae), *C. maculatus*, adapted from Shade et al. 1990; and adults of SO, *S. oryzae*; RD, *R. dominica*, and TC, *T. castaneum*, all adapted from Hagstrum and Flinn (1993).

(Hagstrum and Flinn 1993) were estimated successfully using eight microphones in a 1 kg sample container and checking each sensor for 10 s, 72 times during a 12 min period. Infestation levels of *R. dominica* were estimated by probing a sensor into grain and listening for 20 s at 36 locations (Hagstrum et al. 1990). Infestation levels of *T. castaneum* were estimated in small-scale studies with 16 sensors checked 1,080 times per day (Hagstrum et al. 1991). The number of occurrences of insect sounds in wheat storage bins was correlated with insect density in a study using 140 sensors on 7 cables in grain bins, checking each sensor for 10 s 27 times per day (Hagstrum et al. 1996). Insects present in the wheat storage bins included *R. dominica*, *T. castaneum*, and *S. oryzae*. Acoustic assessments of presence or absence of sugarcane pests could be conducted in 3–5 min periods per sampled position in a sugarcane field, and this was faster than the 10–12 min required to dig up and inspect a sugarcane root system sample (Mankin et al. 2009b).

When the behavior of the cryptic insect or the acoustic properties of the substrate are not well characterized, short assessment periods can lead to high rates of false negatives if the targeted insects cease activity when disturbed; consequently, it is safest to perform at least a few tests over a 10–20 min listening period to determine whether the activity increases with time after the waveguide is inserted into the substrate. Long sampling periods can be helpful also in identifying specific sounds and temporal patterns that discriminate background noise from sounds produced by the targeted species. Conversely, when the substrate strongly attenuates acoustic signals or the insect produces very weak signals, it may be preferable to sample multiple sites rapidly in potential areas of insect presence to determine the best positions from which to detect an infestation. In recent studies of red palm weevil infestations in Curaçao, for example, it was advantageous to sample at multiple locations at different positions along the trunks of palm trees. In ~20 min sampling periods at each tree, it was determined that sounds of many different spectral and temporal patterns could be detected from larvae near the center of infestation, but further away, high-frequency signal attenuation reduced detectability primarily to the fiber-snapping activities that had the highest amplitude and greatest bandwidth. The red palm weevil larvae were not significantly disturbed by insertions of the sensor waveguides into the trunk.

Insect Species and Stages Detected with Different Acoustic Devices

Adults of 16 species, larvae of 40 species, and pseudergates, soldiers, or workers of 10 species have been detected by one or more types of sensor in one or more substrates, including 18 species of stored-product pests in grain or packaged goods (Table 2), 28 wood- or stem-infesting insect species (Table 3), 13 root-feeding insect species (Table 4), and 4 fruit-infesting insect species (Table 5). Species from 21 families and 5 orders have been investigated. Three of the above species and stages were studied using geophone, 7 with condenser microphone, 17 with electret microphone, 12 with an unidentified type of microphone, 31 with PZT contact pickup, 16 with PZT accelerometer, 4 with PVDF piezoelectric film, and 30 with PZT ultrasonic sensors. Most studies on termites were done with ultrasonic PZT. Six of the eight sensor types have been used for detection of *S. oryzae*.

The grain pests *S. oryzae* and *R. dominica* were the two most frequently investigated species. Two invasive, quarantined species also have been investigated frequently: the termite *Coptotermes*

Table 2. Stored-product insect species and stages studied and detection/monitoring devices used

Species (Order: Family)	St[a]	Se[b]	Source
Achroia grisella (F.)	L	p_u	Spangler 1985
(Lepidoptera: Pyralidae)			
Acanthoscelides obtectus (Say)	(A)	p	Andrieu and Fleurat-Lessard 1990
(Coleoptera: Bruchidae)			
Alphitobius diaperinus (Panzer)	L	p	Fleurat-Lessard 1988
(Coleoptera: Tenebrionidae)	(A)	p	Andrieu and Fleurat-Lessard 1990
Anobium punctatum (DeGeer)	L	p	Cross and Thomas 1978
(Coleoptera: Anobiidae)			
Callosobruchus chinensis L.		m	Mori et al. 1962
(Coleoptera: Bruchidae)			
Callosobruchus maculatus (F.)	A	p	Street 1971
(Coleoptera: Bruchidae)	A,L	p_u	Shade et al. 1990
Cylas formicarius elegantulus (Summers)	L	m_c	Hanson 1993
(Coleoptera: Curculionidae)			
Cryptolestes ferrugineus (Stephens)	A	p	Hagstrum and Flinn 1993, Mankin et al. 1997b
(Coleoptera: Laemophoelidae)			
Oryzaephilus surinamensis L.	A	p	Zakladnoi and Ratanova 1986, Hagstrum and Flinn 1993, Mankin et al. 1997a, Schwab and Degoul 2005
(Coleoptera: Silvanidae)			
Plodia interpunctella (Hübner)	L	p	Andrieu and Fleurat-Lessard 1990; Mankin 2002, 2006
(Lepidoptera: Pyralidae)			
Rhyzopertha dominica (F.)	A	p	Street 1971, Zakladnoi and Ratanova 1986, Fleurat-Lessard 1988, Hagstrum and Flinn 1993, Hagstrum et al. 1996, Mankin et al. 1997a
(Coleoptera: Bostrichidae)	L	m_c	Vick et al. 1988b
	L	p	Hagstrum et al. 1988 Hagstrum et al. 1990; Fleurat-Lessard et al. 1994,
	A,L	p	2006; Schwab and Degoul 2005
Sitophilus granarius (L.)	L	p	Bailey and McCabe 1965, Andrieu and Fleurat-Lessard 1990, Weinard 1998
(Coleoptera: Curculionidae)	A,L	p	Zakladnoi and Ratanova 1986, Fleurat-Lessard et al. 1994, Schwab and Degoul 2005
	(A)	p	Welp 1994
Sitophilus oryzae (L.)	A	m_c	Mankin et al. 2010
(Coleoptera: Curculionidae)	A	p	Hagstrum and Flinn 1993, Hagstrum et al. 1996, Mankin et al. 1997a
	A	p_f	Mankin et al. 2010
	L	m	Adams et al. 1953, 1954
	L	m_c	Mankin et al. 1996, Vick et al. 1988a,b
	L	m_c	Drzewiecki and Shuman 2001, Hickling et al. 2000
	L	p	Street 1971; Shuman et al 1993, 1997; Mankin et al. 1997b; Weaver et al. 1997, Weinard 1998, Mankin et al. 1999; Potamitis et al. 2009
	L	p_u	Shade et al. 1990
	A,L	m	Pesho 1954
	A,L	p	Zakladnoi and Ratanova 1986, Fleurat-Lessard et al. 1994, 2006
	A,L	p_u	Pittendrigh et al. 1997
	(A)	m	Brain 1924
		m	Mori et al. 1962
Sitophilus spp.	A,L	p	Fleurat-Lessard 1988
(Coleoptera: Curculionidae)	NR	m	Kennedy and Devereau 1994
Sitotroga cerealella (Olivier)	L	m_c	Vick et al. 1988b
(Lepidoptera: Gelechiidae)	L	p	Street 1971, Andrieu and Fleurat-Lessard 1990, Fleurat-Lessard et al. 1994, Welp 1994, Schwab and Degoul 2005
	L	p_u	Shade et al. 1990
Stegobium paniceum (L.)	A	m_c	Mankin et al. 2010
(Coleoptera: Anobiidae)	A	p_f	Mankin et al. 2010
Tribolium castaneum (Herbst)	A	m_c	Mankin et al. 2010
(Coleoptera: Tenebrionidae)	A	p	Hagstrum et al. 1991, 1996, 1998; Hagstrum and Flinn 1993; Mankin et al. 1997a
	A	p_f	Mankin et al. 2010
Tribolium confusum Jacquelin du Val	A,L	p	Zakladnoi and Ratanova 1986, Schwab and Degoul 2005
(Coleoptera: Tenebrionidae)			
Tribolium spp.	A	p	Fleurat-Lessard 1988
(Coleoptera: Tenebrionidae)	NR	m	Kennedy and Devereau 1994
Zabrotes subfasciatus (Boheman)	L	p_u	Shade et al. 1990
(Coleoptera: Bruchidae)			

[a]Stage: A, adult; L, larva; N, Nymph; NR, not reported; P, pseudergates (false worker); S, soldier, W, worker
[b]Sensor: g = geophone, m = microphone (unknown type), m_c = capacitance (condenser) microphone, m_c = electret microphone, p = contact pickup using PZT piezoelectric transducer, p_a = PZT accelerometer (0-20 kHz), p_f = PVDF piezoelectric film transducer, p_u = PZT ultrasonic transducer (20-200 kHz), t = tachometer

formosanus Shiraki that has recently been spread from Asia to Africa and the U.S., and the red palm weevil that has recently spread from Asia to Arabian, European, and Caribbean countries.

Incorporation of Acoustic Methods into Insect Detection Surveys, Population Estimation, and Mapping Applications

Acoustic methods have been applied successfully in surveys for the presence or absence of targeted insect species (Mankin et al. 2009b, Mankin and Moore 2010), estimations of population density (Hagstrum et al. 1988, 1990, 1991, 1996), and mappings of insect distributions (Brandhorst-Hubbard et al. 2001, Mankin et al. 2007), but it has been necessary to interpret the acoustic signals carefully because they are affected by many environmental and behavioral factors described in sections above. In determining the feasibility of acoustic technology in a particular environment, it is beneficial to have initial knowledge about the acoustic characteristics of the substrate, the types of behavior that the target species performs to produce sounds, the effects of disturbance on sound production, and the temperature range and time of day of greatest activity.

As discussed above in the section on effects of insect size and behavior on acoustic signal production, the sampling statistics for acoustic detection of single species and stage populations at constant temperatures in the laboratory are often similar to those for grain sampling, and this results in the accuracy of insect density estimates made with a representative sample being similar for the two methods. However, insect density may be more difficult to estimate in natural populations and environments where temperatures vary and different species and stages are present. Even in conventional sampling, considerable attention typically is given to determining the number of insects in a grain sample during grain inspection, but less consideration is given to determining whether the sample is representative of the entire lot of grain being inspected. When estimating the number of insects in a grain sample or continuously monitoring for insects, a representative number of locations need to be sampled to estimate overall insect density in a commercial lot of grain, both for conventional and acoustic inspections. Otherwise, overestimation or underestimations of populations may result.

Comparing acoustic estimates with actual counts, acoustic methods overestimated the number of *S. oryzae* larvae in 6% of grain samples (false positives) and underestimated their numbers in 34% of grain samples (false negatives) in a study by Shuman et al. (1993). False positives and false negatives both can be reduced using acoustic signatures, spectral profiles, or temporal pattern analyses (see *Signal Features* section above). In tests with a continuous monitoring device, adult *R. dominica* were identified successfully by their acoustic signatures 73% of the time, with success rates of 72% for *T. confusum*, 63% for *S. granarius*, and 61% for *O. surinamensis* (Schwab and Degoul 2005). The percentages for successful identification of larvae were 73% for *S. granarius*, 58% for *S. cerealella*, 57% for *R. dominica,* and 52% for *T. confusum*.

Typically, prevalence of false positive and negative detections both decrease as insect size increases. False positives are reduced because larger insects tend to produce large numbers of energetic signals with broadband frequency components that are relatively easy to distinguish from low-frequency background noise (Mankin et al. 2010). False negatives are reduced because larger insects can produce louder signals that carry over longer distances to a sensor. Small insects are more likely to be detected if they are present at high densities because the sensors are more likely to be placed within the active space of an insect when the insect is present at high densities in the substrate.

Despite the factors above that may increase the need for numbers or durations of samples, acoustic monitoring has important advantages that enable earlier detection than conventional grain sampling, including the detection of internal feeding larvae and the capability of remote continuous surveillance. Because adults sieved from grain samples represent only 2% *R. dominica* and 5% of *C. ferrugineus* populations, infestations are more likely to be identified if larvae as well as adults are detected (Perez-Mendoza et al. 2004). Automatic continuous monitoring detected insects 3 to 28 d earlier than taking grain samples (Hagstrum et al. 1996).

For Caribbean fruit flies, *Anastrepha suspensa* (Loew) in grapefruit at room temperature, acoustic monitoring for 0.5–10 min intervals daily has been found to be a more reliable detection method than cutting fruit open for visual inspection (Calkins and Webb 1988). Larvae were detected soon after hatch and were detected most readily in mature fruit because they fed more continuously. Continuous acoustic monitoring also was more effective than cutting open cotton bolls for detection of *P. gossypiella* (Hickling et al. 2000). Eighty-six percent of larvae were detected by listening, while only 53% were detected by the conventional method of cutting open and visually inspecting bolls. There were 12% false positives and 4% false negatives using the acoustic method.

The distributions of soil insects have been mapped successfully using acoustic sensors (Brandhorst-Hubbard et al. 2001; Mankin et al. 2001, 2007). Statistically significant associations have been identified between acoustic indicators of infestation likelihood and the measured counts of sound-producing soil invertebrates, and acoustic indicator-based mapping has been used to successfully identify locations needing treatment against white grubs (Mankin et al. 2007).

Development and Marketing of Insect Acoustic Detection and Monitoring Devices.

During the last few decades, various types of acoustic devices have been marketed for detection and monitoring of insect populations (Table 6), including a sample container in a sound-insulated chamber for laboratory use (Sito Detect, Pest-bin detector, EWDLab) and probe sensors for field use. Probes may be pushed directly into a commodity (Larva sound detector and EWD Portable) or may be attached to a waveguide that is inserted into the substrate or commodity (Pest probe detector, Termite tracker, AED-2000, AED-2010, and WD60). Marketing has focused on stored grain insects and termites, but recently has been expanded to pink bollworm and red palm weevil. Pallaske (1990) patented the monitoring of the vibration pattern associated with the behavior of wood-boring insects, and Gobernado et al. (2005) received a similar patent for stored grain insects. Hickling et al. (1994, 1997b, 2000) developed and patented a multisensor box for monitoring pink bollworm, and the Laar WD-60 and other instruments (Siriwardena et al. 2010) have been marketed for detection of red palm weevil in date palm orchards.

Some equipment has been developed but not marketed. Webb and Landolt (1984) and Webb et al. (1988a, b) developed equipment for detecting tephritid larva within fruit, Shuman et al. (1993, 1997), Mankin et al. (1997a, b), and Weaver et al. (1997) developed and Vick et al. (1995) patented equipment and software for detecting stored-product insect larvae feeding inside kernels of grain and Shade et al. (1989, 1990) developed and patented equipment for detect-

Table 3. Wood- or plant-stem infesting insect species and stages studied and detection/monitoring devices used

Species (Order: Family)	St[a]	Se[b]	Source
Agrilus dozieri Fisher	L	p_a	Mankin et al. 2008b
(Coleoptera: Buprestidae)			
Agrilus planipennis Fairmaire	L	p	Chesmore and Schofield 2010
(Coleoptera: Buprestidae)			
Anoplophora glabripennis (Motschulsky)	L	p	Mankin et al. 2008c, Chesmore and Schofield 2010
(Coleoptera: Cerambycidae)			
Anoplophora chinensis (Forster)	L	p	Chesmore and Schofield 2010, This paper
(Coleoptera: Cerambycidae)			
Cephus cinctus Norton	L	m_c	Mankin et al 2000
(Hymenoptera: Cephidae)	L	p_a	Mankin et al 2000, 2004
Coptotermes domesticus Haviland	P,W	p_u	Matsuoka et al. 1996, Indrayani et al. 2003
(Isoptera: Rhinotermitidae)			
Coptotermes formosanus Shiraki	NR	p_u	Noguchi et al. 1991, Robbins et al. 1991, Weissling and Thoms 2000
(Isoptera: Rhinotermitidae)	P	p_u	Scheffrahn et al. 1993
	P,W	p_u	Matsuoka et al. 1996
	S,W	p_a	Mankin et al. 2002
	S,W	p_u	Fujii et al. 1990
	W	p_f	Yanase et al. 1998
	W	p_u	Yanase et al. 2000
		m	Mori et al. 1962
Coryphodema tristis (Frury)	L	m	Brain 1924
(Lepidoptera: Cossidae)			
Cryptotermes brevis (Walker)	NR	p_u	Thoms 2000, Woodrow et al. 2006
(Isoptera: Rhinotermitidae)			
Hylotrupes bajulus (L.)	L	m	Schwarz et al. 1935
(Coleoptera: Cerambycidae)	L	p	Farr and Chesmore 2007, Chesmore and Schofield 2010
Incisitermes minor (Hagen)	A,S,W	p_u	Pence et al. 1954, Lewis et al. 2004
(Isoptera: Kalotermitidae)	P	p_u	Indrayani et al. 2007
	W	p_u	Lemaster et al. 1997
Incisitermes snyderi (Light)	P	p_u	Scheffrahn et al. 1993
(Isoptera: Kalotermitidae)	NR	p_u	Thoms 2000
Lucanus cervus L.	A,L	p	Farr and Chesmore 2007
(Coleoptera: Lucanidae)			
Monochamus titillator (F.)	L	p_a	Mankin et al. 2008b
(Coleoptera: Cerambycidae)			
Nasutitermes luzonicus Oshima	W	p_a	Mankin and Moore 2010
(Isoptera: Termitidae)			
Oryctes rhinoceros (L.)	A,L	p_a	Mankin et al. 2009a, Mankin and Moore 2010
(Coleoptera: Scarabaeidae)			
Neotermes jouteli (Banks)	P	p_u	Scheffrahn et al. 1993
(Isoptera: Kalotermitidae)			
Prionus coriarius (L.)	L	p	Farr and Chesmore 2007
Coleoptera: Cerambycidae			
Reticulitermes flavipes (Kollar)	P	p_u	Scheffrahn et al. 1993
(Isoptera: Rhinotermitidae)	S	m	Emerson 1929
	W	p_a	Mankin et al. 2002
Reticulitermes grassei Clement	S	p_u	De la Rosa et al. 2005
(Isoptera: Rhinotermitidae)			
Reticulitermes hesperus (Banks)	W	p_u	Lemaster et al. 1997
(Isoptera: Rhinotermitidae)			
Reticulitermes lucifugus Rossi	NR	p_u	De la Rosa et al. 2008a, b
(Isoptera: Rhinotermitidae)	S	p_u	De la Rosa et al. 2006
Reticulitermes virginicus Banks	W	p_a	Mankin 2002
(Isoptera: Rhinotermitidae)			
Reticulitermes speratus (Kolbe)	P,W	p_u	Matsuoka et al. 1996
(Isoptera: Rhinotermitidae)			
Rhynchophorus ferrugineus (Olivier)	L	m	Hetzroni et al. 2004
(Coleoptera: Curculionidae)	L	m_c	Gutierrez et al. 2010
	L	p	Abraham et al. 1966, Soroker et al. 2004, Al-Manie and Alkanhal 2005, Mankin et al. 2008b, Hussein et al. 2010, Siriwardena et al 2010
	L	p_u	Pinhas et al. 2008, Potamitis et al. 2009, Sivaraman et al 1989
Trichoferus griseus (Fabricius)	L	p	Chesmore and Schofield 2010
Coleoptera: Cerambycidae			
Xestobium rufovillosum (DeGeer)	L	p	Colebrook 1937, Birch and Menendez 1991
(Coleoptera: Anobiidae)			
Zootermopsis nevadensis (Hagen)	W	p_u	Lemaster et al. 1997
(Isoptera: Termopsidae)			

[a], [b]. see Table 2

ing several internally feeding stored-product insects. Litzkow et al. (1990) patented the use of a piezoelectric sensor on a probe used by Hagstrum et al. (1988, 1990) to detect insects in stored wheat. The same sensor was used in a flow-through, eight-sensor grain sample container in the laboratory (Hagstrum and Flinn 1993), in grain to monitor insect response to a temperature gradient (Hagstrum et al. 1998) and on cables in grain stored in bins (Hagstrum et al. 1996). An advantage of automatic continuous monitoring with sensors in grain is that insects are very mobile, and many will eventually crawl past a sensor. A microphone system was constructed and used to monitor adult population levels in bag storage in Zimbabwe (Kennedy and Devereau 1994). A phonograph pickup system was developed by A. T. Davis (Abraham et al. 1966) to detect red palm weevil.

Many of the marketing efforts have been short-lived, but in some cases, instruments remain available for use with insects because they have other uses as well. For termites, there have been a number of competing devices and some are currently available because the termite industry is very large. Locator and Scout It Out (Potter 2004) are no longer commercially available, but the marketer of Termite Tracker also sells acoustic emission detectors for leaks. The AED-2000 and AED-2010 are marketed for leak detection as well as wood pests. The Laar WD-60 is marketed for medical use as well as for red palm weevil detection. The multisensor box for pink bollworm detection remains commercially available because its marketer also does a broad range of acoustic consulting. This device also has been shown to be effective in detecting tephritid fruit flies and rice weevils. Systelia Technologies plans to sell their Early Warning Device (EWD) to the grain industry in Europe to help meet new regulations requiring a 50% reduction in pesticide use.

The Promise of Future Insect Acoustic Detection and Monitoring Methods and Studies

The need for nondestructive, rapid, and inexpensive means of detecting hidden insect infestations is not likely to diminish in the near future, and there are several areas where acoustic methods are likely to expand to help meet the needs of entomologists, businesses, and regulators. First, the costs of presently available instruments (see above) that provide rapid aural assessment of insect presence or absence will decrease as technology improves. Likely, these will be combined with playback devices, such as iPods or iPhones, which

Table 4. Root-infesting insect species and stages studied and detection/monitoring devices used

Species (Order: Family)	St[a]	Se[b]	Source
Antitrogus parvulus Britton	L	p_a	Mankin et al. 2009b
(Coleoptera: Scarabaeidae)	L	p_u	Mankin et al. 2009b
Camponotus denticulatus Kirby	W	g	Mankin and Benshemesh 2006
(Hymenoptera: Formicidae)			
Cotinis nitida (L.)	L	m_c	Brandhorst et al.2001, Mankin et al. 2007
(Coleoptera: Scarabaeidae)			
Cyclocephala lurida (Bland)	L	m_c	Mankin et al 2000, Zhang 2003a, b
(Coleoptera: Scarabaeidae)	L	p	Mankin et al 2000
	L	p_a	Mankin et al 2000
Cyclocephala spp.	L	m_c	Brandhorst et al.2001
(Coleoptera: Scarabaeidae)	L	m_c	Mankin et al. 2007
Dermolepida albohirtum (Waterhouse)	L	p_a	Mankin et al. 2009a
(Coleoptera: Scarabaeidae)	L	p_u	Mankin et al. 2009a
Diaprepes abbreviatus (L.)	L	m_c	Mankin et al 2000
(Coleoptera: Curculionidae)	L	p	Mankin et al 2000
	L	p_a	Mankin et al 2000, 2001; Mankin and Lapointe 2003
	L	p_u	Mankin and Lapointe 2003
Drepanotermes sp.	W	g	Mankin and Benshemesh 2006
(Isoptera: Termitidae)			
Otiorhynchus sulcatus (F.)	L	m_c	Mankin et al 2000
(Coleoptera: Curculionidae)	L	p	Mankin et al 2000
	L	p_a	Mankin et al 2000, Mankin and Fisher 2002
Phyllophaga congrua (LeConte)	L	m_c	Zhang 2003a
(Coleoptera: Scarabaeidae)			
Phyllophaga crassissima (Blanchard)	L	m_c	Zhang 2003a
(Coleoptera: Scarabaeidae)			
Phyllophaga crinita (Burmeister)	L	m_c	Mankin et al 2000; Zhang 2003a, b
(Coleoptera: Scarabaeidae)	L	p	Mankin et al 2000
	L	p_a	Mankin et al 2000
Phyllophaga spp.	L	m_c	Brandhorst et al. 2001, Mankin et al. 2007
(Coleoptera: Scarabaeidae)	L	p_a	Mankin et al. 2001
Polyphylla spp.	L	m_c	Brandhorst et al.2001, Mankin et al. 2007
(Coleoptera: Scarabaeidae)			
Rhytidoponera taurus (Forel)	W	g	Mankin and Benshemesh 2006
(Hymenoptera: Formicidae)			

[a], [b]. see Table 2

Table 5. Fruit-infesting insect species and stages studied and detection/monitoring devices used

Species (Order: Family)	St[a]	Se[b]	Source
Anastrepha suspensa (Loew)	L	m_c	Calkins and Webb 1988, Sharp et al. 1988, Webb 1988a
(Diptera: Tephritidae)	L	m_c	Hickling et al. 2000
	L	p_a	Webb and Landolt 1984
Ceratitis capitata (Wiedemann) (Diptera: Tephritidae)	L	m_c	Mankin et al. 2006
Dacus dorsalis Hendel (Diptera: Tephritidae)	L	m_c	Hansen et al. 1988
Pectinophora gossypiella Saunders	A	P	Schouest and Miller 1994
(Lepidoptera: Gelechiidae)	L	m_c	Hickling et al. 1994, 2000; Schneider 1995

[a], [b]. see Table 2

can be used by nontechnical personnel to compare what they are hearing with sounds produced by different pest insects. This technology already enables networking among different businesses or regulatory agencies that monitor insects, which permits the tracking of insect infestations in grain and other commodities as they move through the marketing system.

Second, the technology for discriminating insect sounds from noise and for distinguishing among different insect species is likely to improve significantly. Entomologists have begun to make use of standard speech recognition tools like Gaussian mixture models (Pinhas et al. 2008, Potamitis et al. 2009) and hidden Markov models (Mankin et al. 2009b) only recently. This technology should enhance the capability of remote sensing, nondestructive and automated detection, and monitoring tools and trapping systems (Mankin et al. 2006, 2010; Tobin et al. 2009; Potamitis et al. 2009, Siriwardena et al. 2010, Gutiérrez et al. 2010).

Third, acoustic methods are likely to gain broad acceptance for detection of large, active insects hidden in high-value substrates. The use of acoustic sensors may reduce costs by avoiding the needless destruction of the commodity and allowing for more material to be inspected upon importation into the U.S. or other countries. For example, acoustic sensors may provide a more effective means to detect internal woodborers in the buprestid and cerambycid families that are pests of imported Chinese bonsai trees. Currently, inspectors conduct destructive sampling on a random number of this high-value commodity. Acoustic sensors may also aid in surveys for invasive pests that are not known or have recently established in an area. The visual signs of important invasive pests such as emerald ash borer (*Agrilus planipennis* Fairmaire), red palm weevil (Potamitis et al. 2009), and coconut rhinoceros beetle (Mankin and Moore 2010) are very difficult to detect and normally appear in the tree only following severe infestations, when it is too late to prevent their spread. We note, however, that there are some insects for which acoustic detection methods are not likely to be useful, such as quiescent pupae, sedentary insects that feed on plant juices, small larvae like wireworms or rootworms that weigh less than 3–8 mg (Mankin et al. 2004), or insects in fruit that are kept in cold storage, primarily because of low rates of sound production.

Acoustic detection methods may greatly enhance the ability of a surveyor to find and quickly dispose of infested material, thereby increasing the likelihood of a successful eradication program. Acoustic detection systems may be useful in commodity preclearance programs, where an importer would use a system to cull infested material before the product is shipped to another country. In addition, acoustic devices would greatly aid nursery and landscape managers dealing with pests such as red palm weevil (Potamitis et al. 2009) or black vine weevil (Mankin and Fisher 2002) by helping them locate infested nursery stock and by determining if a chemical treatment was effective.

Acoustic methods may be even more important in several low-value commodities like grain, fresh fruit, and cotton because large

Table 6. Marketing of acoustic monitoring devices for insects

Insects: Trade name	Company	Patent
Stored grain insects:		
Sito Detect	France	Busnel and Andrieu 1966, Mihaly 1973
Pest-probe detector	Pestcon Systems, IA	Betts 1991
Pest-bin detector	Pestcon Systems, IA	
Larven Lausher	NIR - Service, Germany	
EWD Portable	Systelia Technologies, France	Gobernado et al. 2005
EWD Lab	Systelia Technologies, France	
Termites:		
Insecto-scope	Sound Technologies, Kilgore, TX	Betts 1990
Locator	Dow AgroSciences, Indianapolis	Robbins and Mueller 1994
Scout It Out	Acoustic Technology Group, Sacramento, CA	
AED-2000	Acoustic Emission Consulting, Fair Oaks, CA	
Termite Tracker	Dunegan Engineering, Midland, TX	Dunegan 2005
Other insects:		
multisensor box	Sonometrics, Huntington Woods, MI	Hickling et al. 1997b
Laar WD60	LaarTech Agric., Germany	

volumes need to be sampled for insects economically. Acoustic methods for these commodities were developed initially for regulatory or food safety agencies, but these methods could be even more important to the industries being regulated. Acoustic methods for detecting and monitoring insect pests also may be useful for turf and packaged, processed commodities.

A full assessment of costs and benefits of acoustic methods is beyond the scope of this report, partly because the costs and benefits are changing rapidly, and partly because no citable studies on the subject have been published. Although they are ultimately important concerns, cost and benefit ratios are not yet the primary issue driving acoustic methods into commercial use. Arguably, the unique capabilities of acoustic methods for automatic, continuous, non-destructive, remote monitoring and detection of hidden infestations are currently the main drivers for acoustic insect detection development. Niche applications already exist where benefits of sensitive, rapid detection justify the costs of instrumentation and signal analysis, and the costs will continue to decline.

Finally, apart from the economic benefits, there are many research questions that can best be answered by using acoustic technology. The feeding and movement activities of internal tree-feeding or subterranean larvae, for example, cannot be studied easily in a nondestructive manner without the use of acoustic methods, X-ray tomography, or similar technology (Johnson et al. 2007).

Acknowledgments

We thank Everett Foreman and Betty Weaver (ARS), Clinton Johanns and Kenneth Heidweiller (Curaçao Department of Agriculture), and Facundo Franken and Teophilo Damien (Aruba Department of Agriculture) for research assistance. Funding for studies in Curaçao and Aruba was provided in part by Section 10201 of the 2008 Farm Bill awarded in 2010.

*The use of trade, firm, or corporation names in this publication does not constitute an official endorsement or approval by the United States Department of Agriculture, Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

References Cited

Abraham, V. A., K. Mathen, and C. Kurian. 1966. Aids to detect red weevil infestation in coconut palm. Coconut Bulletin 20: 148-152.

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

Adams, R. E., J. E. Wolfe, M. Milner, and J. A. Shellenberger. 1954. Detection of internal infestation in grain by sound amplification. Cereal Chem. 31: 271-276.

Al-Manie, M.A., and, M. I. Alkanhal. 2005. Acoustic detection of the red date palm weevil. World Academy of Science, Engineering and Technology 2: 160-163.

Andrieu, A. J., and F. Fleurat-Lessard. 1990. Insect noise in stored foodstuffs. Compact Disk, INRA Ed., Versailles, France.

Anon. 1935. The weevil made audible. Amer. Miller 63: 38.

Au, W. W. 1997. Some hot topics in animal bioacoustics. J. Acoust. Soc. Am. 101: 2433-2441.

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

Barbero, F., J. A. Thomas, S. Bonelli, E., Balletto, and K. Schőnrogge. 2009. Queen ants make distinctive sounds that are mimicked by a butterfly social parasite. Science 323: 782-785.

Betts, W. B. 1990. Destructive insect induced vibration detector. US Patent No. 4,895,025, Jan. 23, 1990.

Betts, W. B. 1991. Apparatus for detecting insect-induced vibrations in particulate matter. US Patent No. 4,991,439, Feb. 12, 1990.

Birch, M., and G. Menendez. 1991. Knocking on wood for a mate. New Scientist 131 (1776): 42-44.

Brain, C. K. 1924. Preliminary note on the adaptation of certain radio principles to insect investigation work. Ann. Univ. Stellenbosch Ser. A 2: 45-47.

Brandhorst-Hubbard, J. L., K. L. Flanders, R. W. Mankin, E. A. Guertal, and R. L. Crocker. 2001. Mapping of soil insect infestations sampled by excavation and acoustic methods. J. Econ. Entomol.94:1452-1458.

Busnel, R. G., and A. J. Andrieu. 1966. Appareil pour la detection d'insectes ou autres parasites dans des produits ou materiaux divers. INRA Patent No. 15 11625.

Cade, W. 1975. Acoustically orienting parasitoids: fly phonotaxis to cricket song. Science 190: 1312-1313.

Calkins, C. O., and J. C. Webb. 1988. Temporal and seasonal differences in movement of Caribbean fruit fly larvae in grapefruit and the relationship to detection by acoustics. Fla. Entomol. 71: 409-416.

Chesmore, E. D., 2001. Application of time domain signal coding and artificial neural networks to passive acoustical identification of animals. Appl. Acoust. 62: 1359-1374.

Chesmore, E. D., and E. Ohya. 2004. Automated identification of field-recorded songs of four British grasshoppers using bioacoustic signal recognition. Bull. Entomol. Res. 94: 319-330.

Chesmore, D. and J. Schofield. 2010. Acoustic detection of regulated pests in hardwood material. EPPO/OEPP Bulletin 40: 46-51

Cocroft, R. B., and R. L. Rodriguez. 2005. The behavioral ecology of insect vibrational communication. Bioscience 55: 323-334.

Čokl, A. 2008. Stink bug interaction with host plants during communication. J. Insect Physiol. 54: 1113-1124.

Colebrook, F. M. 1937. The aural detection of the larvae of insects in timber. J. Scientific Instruments 14: 119-121.

Cross, D. J., and R. S. Thomas. 1978. An acoustic amplifier and activity integrator for laboratory studies on wood borer. Laboratory Practice 27: 567-569.

De la Rosa, J. J. G., I. Lloret, A. Moreno, C. G. Puntonet, and J. M. Gorriz. 2006. Wavelets and wavelet packets applied to detect and characterize transient alarm signals from termites. Measurement 39: 553-564.

De la Rosa, J. J. G., I. Lloret, C. G. Puntonet, R. Piotrkowski, and A. Moreno. 2008a. Higher-order spectra measurement techniques of termite emissions, a characterization framework. Measurement 41: 105-118.

De la Rosa, J. J. G., and A. Munoz. 2008b. Higher-order cumulants and spectral kurtosis for early detection of subterranean termites. Mechanical Systems and Signal Processing 22: 279-294.

De la Rosa, J. J. G., C. G. Puntonet, and I. Lloret. 2005. An application of the independent component analysis to monitor acoustic emission signals generated by termite activity in wood. Measurement 37: 63-76.

Dornfeld, D. A., and E. Kannatey-Asibu. 1980. Acoustic emission during orthogonal metal cutting. Int. J. Mech. Sci. 22: 285-296.

Drosopoulos, S., and M. F. Claridge. 2006. Insect sounds and communication: physiology, behaviour, ecology and evolution. Taylor and Francis, Boca Raton, FL

Drzewiecki, T. M., and D. Shuman. 2001. Acousto-fluidic detection of insect larvae in grain. Acta Hort. (ISHS) 562: 233-241.

Dunegan, H. L. 2005. Detection of movement of termites in wood by acoustic emission techniques. US Patent No. 6,883,375, Apr. 26, 2005.

Dyer, F. D., 1997. Edison, his life and inventions. World Wide School. Seattle, WA.

Emerson, A. E., and R. C. Simpson. 1929. Apparatus for the detection of substratum communication among termites. Science 69: 648-649.

Escherich, K. 1911. Termitenleben auf Ceylon. Gustav Fischer, Jena.

Farr, I., and D. Chesmore. 2007. Automated bioacoustic detection and identification of wood-boring insects fro quarantine screening and insect ecology. Proc. Institute Acoustics. 29: 201-208.

Fleurat-Lessard, F. 1988. Determination of insect infestation. p 495-515. In J. L. Multon, A. M. Reimbert, D. Marsh and A. J. Eydt (eds) Preservation and storage of grains, seeds and their products: cereals, oilseeds, pulses and animal feed. Lavoisier Publishing Inc., New York.

Fleurat-Lessard, F., A.-J. Andrieu, and D. R. Wilkin. 1994. New trends in stored-grain infestation detection inside storage bins for permanent infestation risk monitoring, pp. 397-402. In E. Highley, E. J. Wright, H. J.

Banks, and B. R. Champ [eds.], Stored product protection: Proceedings, 6th International Working Conference on Stored-Product Protection, vol. 1. CAB International, Oxon, United Kingdom.

Fleurat-Lessard, F., B. Tomasini, L. Kostine, and B. Fuzeau. 2006. Acoustic detection and automatic identification of insect stages activity in grain bulks by noise spectra processing through classification algorithms, pp. 476-486. In I. Lorini, B. Bacaltchuk, H. Beckel, D. Deckers, E. Sundfeld, J. P. Dos Santos, J. D. Biagi, J. C. Celaro, L. R. D'A Faroni, L. de., and O. F. Bortolini (eds.), Proc. 9th International Working Conference on Stored Product Protection, October 15-18, 2006, Sao Paulo Brazil 2006.

Forrest, T. G. 1988. Using insect sounds to estimate and monitor their populations. Fla. Entomol. 71: 416-426.

Fujii, Y., M. Noguchi, Y. Imamura, and M. Tokoro. 1990. Using acoustic emission monitoring to detect termite activity in wood. Forest Products J. 40: 34-36.

Gautschi, G. 2002. Piezoelectric sensorics: Force, strain, pressure, acceleration and acoustic emission sensors, materials and amplifiers, 259 pp. Springer-Verlag, Berlin Germany.

Gobernado, P. R., F. Fleurat-Lessard, J. Villamayor, B. Sautereau, G. Brioni, J. Gondolo, and B. Tomasini. 2005. Method and device for detection, identification and densimetric quantification of grain-eating insects in stocks of cereals. US Patent No.: 6,923,064 B2, August 2, 2005.

Guo, M., Z. Shang, and H. Shi. 2005. Sound absorption measurements of various types of grain. Acta Acustica 91: 915-919.

Gutiérrez, A., V. Ruiz, E. Moltó, G. Tapia, and M. del Mar Téllez. 2010. Development of a bioacoustic sensor for the early detection of red palm weevil (*Rhynchophorus ferrugineus* Olivier). Crop Prot. 20: 671-676.

Haack, R. A., R. W. Blank, F. T. Fink, and W. J Mattson. 1988. Ultrasonic acoustical emissions from sapwood of eastern white pine, northern red oak, red maple, and paper birch: implications for bark- and wood-feeding insects. Fla. Entomol. 71: 427-440.

Hagstrum, D. W., and P. W. Flinn. 1993. Comparison of acoustical detection of several species of stored-grain beetles (Coleoptera: Curculionidae, Tenebrionidae, Bostrichidae, Cucujidae) over a range of temperatures. J. Econ. Entomol. 86: 1271-1278.

Hagstrum, D. W., P. W. Flinn, and J. Gaffney. 1998. Temperature gradient on *Tribolium castaneum* (Coleoptera: Tenebrionidae) adult dispersal in stored wheat. Environ. Entomol. 27: 123-129.

Hagstrum, D. W., and Bh. Subramanyam. 2006. Fundamentals of Stored Product Entomology, AACC International, St. Paul, MN.

Hagstrum, D. W., P. W. Flinn, and D. Shuman. 1996. Automated monitoring using acoustical sensors for insects in farm-stored wheat. J. Econ. Entomol. 89: 211-217.

Hagstrum, D. W., K. W. Vick, and P. W. Flinn. 1991. Automated acoustical monitoring of *Tribolium castaneum* (Coleoptera: Tenebrionidae) populations in stored wheat. J. Econ. Entomol. 84: 1604-1608.

Hagstrum, D. W., K. W. Vick, and 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, and K. W. Vick. 1988. Acoustical detection and estimation of *Rhyzopertha dominica* (F.) larval populations in stored wheat. Fla. Entomol. 71: 441-447.

Hansen, J. D. 1993. Acoustical detection of the sweetpotato weevil (Coleoptera: Curculionidae) in sweet potato. J. Entomol. Sci. 28: 453-461.

Hansen, J. D., J. C. Webb, J. W. Armstrong, and S. A. Brown. 1988. Acoustical detection of oriental fruit fly (Diptera: Tephritidae) larvae in papaya. J. Econ. Entomol. 81: 963-965.

Hetzroni, A., A. Mizrach, Y. Nakache, and V. Soroker. 2004. Developing spectral model to monitor activity of red palm weevil. Alon Hanotea 58: 466-469.

Hickling, R., and W. Wei, 1995. Sound transmission in stored grain. Appl. Acoustics 45: 1-8.

Hickling, R., W. Wei, and D. W. Hagstrum. 1997a. Studies of sound transmission in various types of stored grain for acoustic detection of insects. Appl. Acoustics 50: 263-278.

Hickling, R., P. Lee, W. Wei, M. W. Geyer, D. Pierce, R. Staten, and T. Henneberry. 1994. Multiple acoustic sensor system for detecting pink bollworm in bolls. *In* Proceedings, 1994 Beltwide Cotton Conference, Phoenix, AZ., National Cotton Council, Memphis, TN.

Hickling, R., P. Lee, W. Wei, and S. Chang. 1997b. Acoustic sensor system for insect detection. US Patent No. 5,616,845, Apr. 1, 1997.

Hickling, R., P. Lee, D. Velea, T. J. Dennehy, and A. I. Patin. 2000. Acoustic system for rapidly detecting and monitoring pink bollworm in cotton bolls. *In* Proceedings, 2000 Beltwide Cotton Conference, San Antonio, TX, National Cotton Council, Memphis, TN.

Hill, P. S. M. 2008. Vibrational Communication in Animals. Harvard, Cambridge, London.

Hu, X. P., A. G. Appel, and J. F. A. Traniello. 2003. Behavioral response of two subterranean termites (Isoptera: Rhinotermitidae) to vibrational stimuli. J. Insect. Behav. 16: 703-715.

Hussein, W. B., M. A. Hussein, and T. Becker. 2010. Detection of the red palm weevil, *Rhynchophorus ferrugineus* using its bioacoustics features. Bioacoustics 19: 177-194.

Indrayani, Y., T. Yoshimura, Y. Yanase, Y. Fujii, and Y. Imamura. 2007. Evaluation of the temperature and relative humidity preferences of western dry-wood termite *Incisitermes minor* (Hagen) using acoustic emission (AE) monitoring. J. Wood Sci. 53: 76-79.

Indrayani, Y. T. Nakayama, Y. Yanase, Y. Fujii, T. Yoshimura, and Y. Imamura. 2003. Feeding activities of the dry-wood termite *Cryptotermes domesticus* (Haviland) under various relative humidity and temperature conditions using acoustic emission monitoring. Jpn. J. Environ. Entomol. Zool. 14: 205-212.

Johnson, S. N., J. W. Crawford, P. J. Gregory, D. V. Grinev, R. W. Mankin, G. J. Masters, P. J. Murray, D. H. Wall, and X. Zhang. 2007. Non-invasive techniques for investigating and modelling root-feeding insects in managed and natural systems. Agric. Forest Entomol. 9: 39-46.

Kennedy, L., and A. D. Devereau. 1994. Observations on large-scale outdoor maize storage in jute and woven polypropylene sacks in Zimbabwe. p. 290-295. *In* Highley, E., Wright, E. J., Banks, H. J., and Champ, B. R. (eds) Proc. 6th International Working Conference on Stored-Product Protection (Canberra, Australia). CAB International, Wallingford, U.K.

Kisternaya M.V., and V. A. Kozlov. 2009. Wood-science approach for the preservation of historic timber structures. http://www.woodculther.com/wp-content/uploads/2009/09/Kisternaya-Kozlov1.pdf

Lampson, B., Y. Han, A. Khalilian, J. Greene, R. W. Mankin, and E. Foreman. 2010. Characterization of substrate-borne vibrational signals of *Euschistus servus* (Heteroptera: Pentatomidae). Amer. J. Agric. Biol. Sci. 5: 32-36.

Lemaster , R . L ., F . C . Beall , and V . R Lewis. 1997. Detection of termites with acoustic emission. Forest Products Journal 47(2): 75-79 .

Lewis, V. R., A. B. Powell, and M. I. Haverty. 2004. Surface and subsurface sensor performance in acoustically detecting the western drywood termite in naturally infested boards. Forest Products Journal 54(6): 57-62.

Litzkow, C.A., J.C. Webb, and K.W. Vick. 1990. Piezoelectric apparatus and process for detection of insect infestation in an agricultural commodity. US Patent No.: 4,937,555, June 26, 1990.

Lutz, F. E. 1924. Insect sounds. Bull. Amer. Mus. Nat. Hist. 50: 333-372.

Main, F. 1909. La destruction des fourmis blanches. J. Agric. Tropicale 101: 350.

Macatee, S. R. 1995. Considerations in grounding and shielding audio devices. J. Audio Eng. Soc. 43: 472-483.

Mankin, R. W. 1994. Acoustical detection of *Aedes taeniorhynchus* swarms and emergence exoduses in remote salt marshes. J. Am. Mosq. Cont. Assoc. 10: 302-308.

Mankin, R. W. 2002. Increase in acoustic detectability of *Plodia interpunctella* (Lepidoptera: Pyralidae) larvae in stored products after electrical stimulation. Fla. Entomol. 85: 524-526.

Mankin, R. W. 2006. Increase in acoustic detectability of *Plodia interpunctella* larvae after low-energy microwave radar exposure. Fla. Entomol. 89: 416-418.

Mankin, R. W., and J. Benshemesh. 2006. Geophone detection of subterranean termite and ant activity. J. Econ. Entomol. 99: 244-250.

Mankin, R. W., J. Brandhorst-Hubbard, K. L. Flanders, M. Zhang, R. L. Crocker, S. L. Lapointe, C. W. McCoy, J. R. Fisher, and D. K. Weaver. 2000. Eavesdropping on insects hidden in soil and interior structures of plants. J. Econ. Entomol. 93: 1173-1182.

Mankin, R. W., and J. R. Fisher. 2002. Acoustic detection of black vine weevil, *Otiorhynchus sulcatus* (Fabricius) (Coleoptera: Curculionidae) larval infestations in nursery containers. J. Environ. Hort. 20: 166-170.

Mankin, R. W., R. D. Hodges, H. T. Nagle, C. Schal, R. M. Pereira, and P. G. Koehler. 2010. Identification of Stored Product and Urban Insect Pests by Inexpensive Infrared, Acoustic, and Vibrational Detection of Movement. J. Econ. Entomol. 103: 1636-1646.

Mankin, R. W., J. L. Hubbard, and K. L. Flanders. 2007. Acoustic indicators for mapping infestation probabilities of soil invertebrates. J. Econ. Entomol. 100:790-800.

Mankin, R. W., S. N. Johnson, D. V. Grinev, and P. J. Gregory 2008a. Chapter 2. New experimental techniques for studying root herbivores, pp. 20-32. *In* S. N. Johnson and P. J. Murray, (eds.) Root Feeders, an Ecosystem Perspective, CABI, Oxon, UK.

Mankin, R. W., and S. L. Lapointe. 2003. Listening to the larvae. Acoustic detection of *Diaprepes abbreviatus* (L.). Proc Fla. State Hort. Soc. 116: 304-308.

Mankin, R. W., S. L. Lapointe, and R. A. Franqui. 2001. Acoustic surveying of subterranean insect populations in citrus groves. J. Econ. Entomol. 94: 853-859.

Mankin, R. W., R. Machan, and R. Jones. 2006. Field testing of a prototype acoustic device for detection of Mediterranean fruit flies flying into a trap, pp. 165-169. *In* Proc. 7th International Symposium on Fruit Flies of Economic Importance, September 10-15-2006, Salvador, Brazil.

Mankin, R. W., A. Mizrach, A. Hetzroni, S. Levsky, Y. Nakache, and V. Soroker. 2008b. Temporal and spectral features of sounds of wood-boring beetle larvae: identifiable patterns of activity enable improved discrimination from background noise. Fla. Entomol. 91: 241-248.

Mankin, R. W., and A. Moore. 2010. Acoustic detection of *Oryctes rhinoceros* (Coleoptera: Scarabaeidae: Dynastinae) and *Nasutitermes luzonicus* (Isoptera: Termitidae) in palm trees in urban Guam. J. Econ. Entomol. 103: 1135-1143.

Mankin, R.W., A. Moore, P.R. Samson, and K.J. Chandler 2009a. Acoustic characteristics of Dynastid beetle stridulations. Florida Entomologist. 92: 124-133.

Mankin, R. W., W. L. Osbrink, F. M. Oi, and J. B. Anderson. 2002. Acoustic detection of termite infestations in urban trees. J. Econ. Entomol. 95: 981-988.

Mankin, R. W., P. R. Samson, and K. J. Chandler. 2009b. Acoustic detection of Melolonthine larvae in Australian sugarcane. J. Econ. Entomol. 102: 1523-1535.

Mankin, R. W., Shuman, D., and Coffelt, J. A. 1996. Noise shielding of acoustic devices for insect detection. J. Econ. Entomol. 89: 1301-1308.

Mankin, R. W., Shuman, D., and Coffelt, J. A. 1997a. Acoustic counting of adult insects with different rates and intensities of sound production in stored wheat. J. Econ. Entomol. 90: 1032-1038.

Mankin, R. W., Shuman, D., and Weaver, D. K. 1999. Thermal treatments to increase acoustic detectability of *Sitophilus oryzae* (Coleoptera: Curculionidae) larvae. J. Econ. Entomol. 92: 453-462.

Mankin, R. W., M. T. Smith, J. M. Tropp, E. B. Atkinson, and D. Y. Jong. 2008c. Detection of *Anoplophora glabripennis* (Coleoptera: Cerambycidae) larvae in different host trees and tissues by automated analyses of sound-impulse frequency and temporal patterns. J. Econ. Entomol. 101: 838-849.

Mankin, R. W., J. S. Sun, D. Shuman, and D. K. Weaver. 1997b. Shielding against noise interfering with quantitation of insect infestations by acoustic detection systems in grain elevators. Appl. Acoust. 50: 309-324.

Mankin, R. W., D. K. Weaver, M. Grieshop, B. Larson, and W. L. Morrill. 2004. Acoustic system for insect detection in plant stems: Comparisons of *Cephus cinctus* in wheat and *Metamasius callizona* in bromeliads. J. Agr. Urban. Entomol. 21: 239-248.

Matsuoka, H., Y. Fujii, S. Okumura, Y. Imamura, and T. Yoshimura. 1996. Relationship between the type of feeding behavior of termites and acoustic emission (AE) generation. Wood Res. 83: 1-7.

Meyhöfer, R., and J. Casas. 1999. Vibratory stimuli in host location by parasitic wasps. J. Insect Physiol. 45: 967-971.

Michelsen, A., and O. N. Larsen. 1978. Biophysics of the ensiferan ear. I. Tympanal vibrations in bushcrickets (Tettigoniidae) studied with laser vibrometry. J. Comp. Physiol. 123: 193-203.

Mihaly, M. 1973. Procede et dispositif pour rechercher la presence d'insectes nuisibles. Patent No. 77 11393.

Miyatake, T., K. Tabuchi, K. Sasaki, K. Okada, K. Katayama, and S. Moriya. 2008. Pleiotropic antipredator strategies, fleeing and feigning death, correlated with dopamine levels in *Tribolium castaneum*. Anim. Behav. 75: 113-121

Mori, H., M. Kumagai, and K. Hirokawa. 1962. On the frequency of the sounds caused by activities of some kinds of insects. Sci. Rep. Hiyoshi Papers 3: 88-96.

Noguchi, M., Y. Fujii, M. Owada, Y. Imamura, M. Tokoro, and R. Tooya. 1991. AE monitoring to detect termite attack on wood of commercial dimension and posts. Forest Prod. J. 41: 32-36.

Pallaske, M. 1990. Process for detecting insects. US Patent No. 4,941,356, Jul. 17, 1990.

Pence, R. J., S. J. Magasin, and R. G. Nordberg. 1954. Detecting wood-boring insects. California Agri. 8(11): 5.

Perez-Mendoza, J., P. W. Flinn, J. F. Campbell, D. W. Hagstrum, and J. E. Throne. 2004. Detection of stored-grain insect infestation in wheat transported in railroad hopper-cars. J. Econ. Entomol. 97: 1474-1483.

Pesho, G. R. 1954. Detection of immature rice weevils, *Sitophilus oryzae* L. (Curculionidae, Coleoptera), by audio amplification. MS Department of Entomology, Kansas State College of Agriculture and Applied Science, Manhattan, KS.

Pinhas, J., V. Soroker, A. Hetzroni, A. Mizrach, M. Teicher, and J. Goldberger. 2008. Automatic acoustic detection of the red palm weevil. Computers and Electronics in Agriculture 63: 131-139.

Pittendrigh, B. R., J. E. Huesing, R. E. Shade, and L. L. Murdock. 1997. Monitoring of rice weevil, *Sitophilus oryzae*, feeding behavior in maize seeds and the occurrence of supernumerary molts in low humidity conditions. Entomol. Exp. Appl. 83: 225-231.

Potamitis, I., T. Ganchev, and D. Kontodimas. 2009. On automatic bioacoustic detection of pests: the cases of *Rhynchophorus ferrugineus* and *Sitophilus oryzae*. J. Econ. Entomol. 102: 1681-1690.

Potter, M. F. 2004. Termites. p. 217-362. *In* Dan Moreland and Stoy A. Hedges (eds.) Handbook of Pest Control, The Behavior, Life History and Control of Household Pests, 9th edition, Mallis Handbook and Technical Training Co.

Rajendran, S. 1999. Detection of insect infestation in stored food commodities. J. Food Sci. Technol. 36: 283-300.

Reynolds, D. R., and J. R. Riley. 2002. Remote-sensing, telemetric and computer-based technologies for investigating insect movement: a survey of existing and potential techniques. Computers and Electronics in Agriculture 35: 271-307.

Robbins, W. P., R. K. Mueller, T. Schaal, and T. Ebeling. 1991. Characteristics of acoustic emission signals generated by termite activity in wood, pp 1047-1051. In Proceedings IEEE Ultrasonics Symposium, 8-11 December 1990, Orlando, FL.

Robbins, W. P., and R. K. Mueller. 1994. System for detecting wood-destroying insect infestations in wood. US Patent No. 5,285,688, Feb. 15, 1994.

Rudinsky, J. A., and R. R. Michael. 1973. Sound production in Scolytidae: Stridulation by female *Dendroctonus* beetles. J. Insect Physiol. 19: 689-705.

Sanborn, A. F. 2006. Acoustic signals and temperature. pp. 111-125. *In* S. Drosopoulos and F. Claridge (eds) Insect sounds and communication. CRC Taylor and Francis, N. Y.

Scheffrahn, R.H., W.P. Robbins, P. Busey, N.Y. Su, and R.K. Mueller. 1993. Evaluation of a novel, hand-held, acoustic emissions detector to monitor termites (Isoptera: Kalotermitidae, Rhinotermitidae) in wood. J. Econ. Entomol. 86: 1720–1729.

Schneider, K. 1995. Acoustical detection of pink bollworms in cotton bolls. Beltwide Cotton Conference 2: 1054-1057.

Schouest, L. P., and T. A. Miller. 1994. Automated pheromone traps show male pink bollworm (Lepidoptera: Gelechiidae) mating response is dependent upon weather conditions. J. Econ. Entomol. 87: 965-974.

Schwab, L., and P. Degoul. 2005. Automatic acoustical surveillance system of grains in silos. In Fleurat-Lessard, F., Ndiaye, A., Knight, J.D. (Ed.) Stored malting barley: management of quality using an expert system. INRA-Editions, Paris, France, pp. 203-218.

Schwarz, L., Kranz, and Sicke. 1935. A sound amplifier for the detection of infestations by the house beetle. Deutsche Bauzeitung 20: 392-393.

Sessler, G. M., and J. E. West. 1962. Self-biased condenser microphone with high capacitance. J. Acoust. Soc. Am. 34: 1787-1788.

Shade, R. E., E. S. Furgason, and L. Murdock. 1989. Ultrasonic insect detector. US Patent No. 4,809,554, Mar. 7, 1989.

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

Sharp, J. L., R. K. Thalman, J. C. Webb, and S. Masuda. 1988. Flexible acoustical device to detect feeding sounds of Caribbean fruit fly (Diptera: Tephritidae) larvae in mango, cultivar Francis. J. Econ. Entomol. 81: 406-409.

Shuman, D., Coffelt, J. A., Vick, K. W., and Mankin, R. W. 1993. Quantitative acoustical detection of larvae feeding inside kernels of grain. J. Econ. Entomol. 86: 933-938.

Shuman, D., Weaver, D. K., and Mankin, R. W. 1997. Quantifying larval infestation with an acoustical sensor array and cluster analysis of cross-correlation outputs. Appl. Acoust. 50: 279-296.

Siriwardena, K. A. P., L. C. P. Fernando, N. Nanayakkara, K. F. G. Perera, A. D. N. T. Kumara, and T. Nanayakkara. 2010. Portable acoustic device for detection of coconut palms infested by *Rynchophorus ferrugineus* (Coleoptera: Curculionidae). Crop Protection 29: 25-29.

Sivaraman, K., R. S. Moni, and S. C. P. Ramachandran. 1989. Red palm weevil detector. Invention Intelligence 24: 32-35.

Snyder, T. E. 1935. Our enemy the termite. Comstock Publishing Company, Ithaca, N. Y.

Snyder, T. E. 1952. Detection of termites by microphone. Pest Control 20: 33-34.

Soroker, V., Nakash, Y., Landau, U., Mizrach, A., Hetzroni, A., Gerling, D., 2004. Utilization of sounding methodology to detect infestation by *Rhynchophorus ferrugineus* on palm offshoots. Phytoparasitica 32: 6–8.

Spangler, H. G. 1985. Detecting lesser wax moths acoustically. Gleaning Bee Culture 113 (4): 297-209, 218.

Spangler, H. G. 1988. Moth hearing, defense, and communication. Ann. Rev. Entomol. 33: 59-81.

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

Stewart, K. W. 1997. Vibrational communication in insects, epitome in the language of stoneflies? Amer. Entomol. 43: 81-91.

Strübing, H. 2006. Vibratory communication and mating behaviour in the European lantern fly, *Dictyophara europea* (Dictyopharidae, Hemiptera), pp. 351-355. *In* S. Drosopoulos and M. F. Claridge [Eds.]. Insect sounds and communication. Taylor and Francis, Boca Raton, FL.

Sueur, J., S. Pavoine, O. Hamerlynck, and S. Duvail. 2008. Rapid acoustic survey for biodiversity appraisal. PLoS One 3:e4065.

Thoms, E. M. 2000. Use of an acoustic emissions detector and intragallery injection of spinosad by pest control operators for remedial control of drywood termites (Isoptera: Kalotermitidae). Fla. Entomol. 83: 64-74.

Thorne, B. L. 1993. Alternative approaches to termite detection and control. Pest Management 12: 8-16.

Tobin, P. C. K. T. Klein and D. S. Leonard. 2009. Gypsy moth (Lepidoptera: Lymantriidae) flight behavior and phenology based on field-deployed automated pheromone-baited traps. Environ. Entomol. 38: 1555-1562.

Virant-Doberlet, M., and A. Čokl. 2004. Vibration communication in insects. Neotropical Entomol. 33: 121-134.

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

Vick, K. W., C. A. Litzkow, and D. Shuman. 1995. Acoustic location fixing insect detector. US Patent No. 5,473,942, Dec. 12, 1995.

Walker, T. J. 1988. Acoustic traps for agriculturally important insects. Florida Entomol. 71 (4): 484-492.

Walker, T. J. 1996. Acoustic methods of monitoring and manipulating insect pests and their natural enemies. *In* Pest management in the subtropics. Integrated Pest Management: A Florida perspective. Intercept Ltd. Andover, UK.

Weaver, D. K., Shuman, D., and Mankin, R. W. 1997. Optimizing and assessing the performance of an algorithm that cross-correlates acquired acoustic emissions from internally feeding larvae to count infested wheat kernels in grain samples. Appl. Acoust. 50: 297-308.

Webb, J. C., and P. J. Landolt. 1984. Detecting insect larvae in fruit by vibrations produced. J. Environ. Sci. Health A19: 367-375.

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

Webb. J. C., D. C. Slaughter, and C. A. Litzkow. 1988b. Acoustical system to detect larvae in infested commodities. Fla. Entomol. 71: 492-504.

Weinard, W. 1998. Larvae eavesdropper - or where the beetles suddenly appear from. Muhle + Mischfuttertechnik 135: 654.

Weissling, T. J., and E. M. Thoms. 2000. Use of an acoustic emission detector for locating Formosan subterranean termite (Isoptera: Rhinotermitidae) feeding activity when installing and inspecting aboveground termite bait stations containing hexaflumuron. Fla. Entomol. 82: 60-71.

Welp, H. 1994. Acoustic detection of hidden larvae of several storage pests in products from bioshops of Berlin. Thesis Humboltuniversitat, Berlin.

Wessel, A. 2006. Stridulation in the Coleoptera: an overview. pp. 397-403. *In* S. Drosopoulos and M. F. Claridge (eds.) Insect sounds and communication: physiology, behaviour, ecology, and evolution. CRC Press, Taylor & Francis Group, Boca Ration, FL.

Woodrow, R. J., J. K. Grace, and R. J. Oshiro. 2006. Comparison of localized injections of spinosad and selected insecticides for control of *Cryptotermes brevis* (Isoptera: Kalotermitidae) in naturally infested structural mesocosms. J. Econ. Entomol. 99: 1354-1362.

Yanase, Y., Y. Fujii, S. Okumura, and Y. Imamura. 1998. Detection of AE generated by the feeding activity of termites using PVDF (polyvinylidene fluoride) film. Forest Products Journal 48(7): 43-46.

Yanase, Y., Y. Fujii, S. Okumura, and T. Yoshimura. 2000. Plate-type waveguides for detecting acoustic emissions generated by termite attacks. J. Wood Sci. 46: 243-247.

Zakladnoi, G. A., and V. F. Ratanova. 1986. Stored-grain pests and their control. Amerind Publishing Co. Pvt. Ltd, New Delhi.

Zhang, M., R. L. Crocker, R. W. Mankin, K. L. Flanders, and J. L. Brandhorst-Hubbard. 2003a. Acoustic identification and measurement of activity patterns of white grubs in soil. J. Econ. Entomol. 96: 1704-1710.

Zhang, M., R. L. Crocker, R. W. Mankin, K. L. Flanders, and J. L. Brandhorst-Hubbard 2003b. Acoustic estimation of infestations and population densities of white grubs (Coleoptera: Scarabaeidae) in turfgrass. J. Econ. Entomol. 96: 1770-1779.

Zuk, M., and G. R. Kolluru. 1998. Exploitation of sexual signals by predators and parasitoids. Quart. Rev. Biol. 73: 415-438.

Žunič, A., A. Čokl, M. V. Doberlet, and J. G. Millar. 2008. Communication with signals produced by abdominal vibration, tremulation, and percussion in *Podisus maculiventris* (Heteroptera: Pentatomidae). Ann. Entomol. Soc. Am. 101: 1169-1178.

Richard W. Mankin is a Research Entomologist with USDA-ARS at the Center for Medical, Agricultural, and Veterinary Entomology, Gainesville, FL. He focuses on development and application of technology for detection and control of insect infestations, and considers also how insects use olfaction and mechanoreception in communication. **David W. Hagstrum** served as a Research Entomologist at the USDA-ARS Center for Grain and Animal Health, Research, Manhattan, KS for 30 years. As an adjunct emeritus professor at Kansas State University, he continues with studies of stored product insect behavior and ecology. **Michael T. Smith** is a Research Entomologist at the USDA-ARS Beneficial Insects Introduction Unit, Newark, DE. He conducts research on the behavior and ecology of invasive insect species, with an emphasis on early detection. **Amy L. Roda** is an entomologist with USDA-APHIS-CPHST at the ARS Subtropical Horticulture Research Station, Miami, FL. She develops and evaluates biological control technology for early detection of invasive pests in the Caribbean region. **Moses T. K. Kairo** is Director of the Center for Biological Control, Florida A&M University, Tallahassee, FL. He conducts research on early detection and management of invasive insect species.