17

Acoustic methods of monitoring and manipulating insect pests and their natural enemies

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Pertinent properties of hearing and sound

Sensory modalities – such as olfaction, vision, and hearing – offer access to the insect nervous system and the opportunity to modify the insect's behavior to our benefit. Because these senses have been enhanced by natural selection as beneficial windows for the insect to its environment, very small input can have a dramatic effect. A few nanograms of pheromone, in the right context, can attract a male moth to its mate or to its death. A flash of a penlight (simulating a female firefly) can attract a firefly male from 30 meters. The lesson of these examples is that when the sense is acute and when there is some normally adaptive behavior that can be induced, a weak sensory input may yield large results. This has important implications for using acoustic methods to monitor and manipulate pests and their natural enemies. Those pests and enemies that have evolved acute hearing in relation to some environmental threat or opportunity are the ones that are likely to be influenced by weak sounds – which include strong sounds at even moderate distances from the source.

Sound is a series of compressions and rarefactions traveling through an elastic medium. The medium of chief concern in this chapter is air. Certain properties of sound are important to its potential for monitoring and manipulating insects.

How rapidly sound diminishes with distance from the source is a major concern in using sound. There is always a spreading loss – because the same sound power must move more molecules as the surface of the sound field expands with distance. In a free field (i.e., no obstacles or discontinuities in the medium) sound loses ¾ of its intensity (watts/m^2) with each doubling of distance and ½ of its sound pressure (root mean square

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pressure in Newtons/m^2). In addition to spreading loss, there is "excess attenuation" due to absorption in the medium. Higher frequencies are much more subject to excess attenuation that lower ones. For example, such loss more than doubles between 4 and 8 kHz and doubles again at about 12 kHz (Michelsen and Nocke, 1974). In practice, sound fields are not free, and there may be gain or loss through reflection, loss through scattering by obstacles and loss by ground attenuation. The latter is very important when the sound source and sound receiver are both on or near the ground.

Unlike chemicals in air, sound in air generally spreads rapidly in all directions. Unlike light, sound is propagated around obstacles (such as leaves and twigs) – provided its wavelength is substantially greater than the width of the object. On the other hand, sound may not reach a receiver near the ground when the air near the ground is warmer than that above – because sounds are refracted upward by faster propagation in the warmer air. Unlike chemicals but similar to light, sound is transient – it must be continually generated if the signal is to be maintained. This permits easy, short-term, temporal coding (compare signalling by turning a light or a sound on and off with doing the same with a chemical). Long-distance acoustic signalling is generally more expensive energetically than long-distance signalling with chemicals, reflected sunlight, or bioluminescence. This is particularly true for insects because they are small and can therefore produce only high-frequency sounds, which are rapidly absorbed and do not propagate well around obstacles. This, and the danger of being acoustically detected by enemies, may well explain why acoustic communication at distances of a meter or more is rare in insects and why males are generally the broadcasting sex. (Ready-to-mate females are likely to be in short supply relative to ready-to-mate males, causing males to compete for matings.)

Several recent books give good accounts of bioacoustics – viz. Lewis (1983), Ewing (1989), and Bailey (1991).

In this chapter I first discuss methods that depend on attraction to sound, then those that depend on repulsion, and finally those that depend on the detection of insect-generated sounds.

Attraction

If a species exhibits long-range phonotaxis to some natural sound, that species is subject to being lured to a trap baited with that sound. Although few pests and natural enemies are known to exhibit long-range phonotaxis, of those that do, a number have been trapped in large numbers with important benefits. These benefits include collecting living specimens for research or as hosts for rearing biocontrol agents, dispersing biocontrol agents, aiding field studies of populations, and suppressing populations. Before describing the utility and limitations of sound traps, I will deal with their construction and operation.

Sound traps

Seven years ago I reviewed the theory and technology of sound-baited traps (Walker, 1988). Here I will repeat the essentials and describe recent progress.

The principal parts of any sound trap are likely to be a sound source, a catching device, and a controller. The latter can be omitted if the researcher is willing to operate the trap manually or let it run continuously. How these components may be combined is illustrated in Figure 1, which shows a standard trapping station used in mole cricket

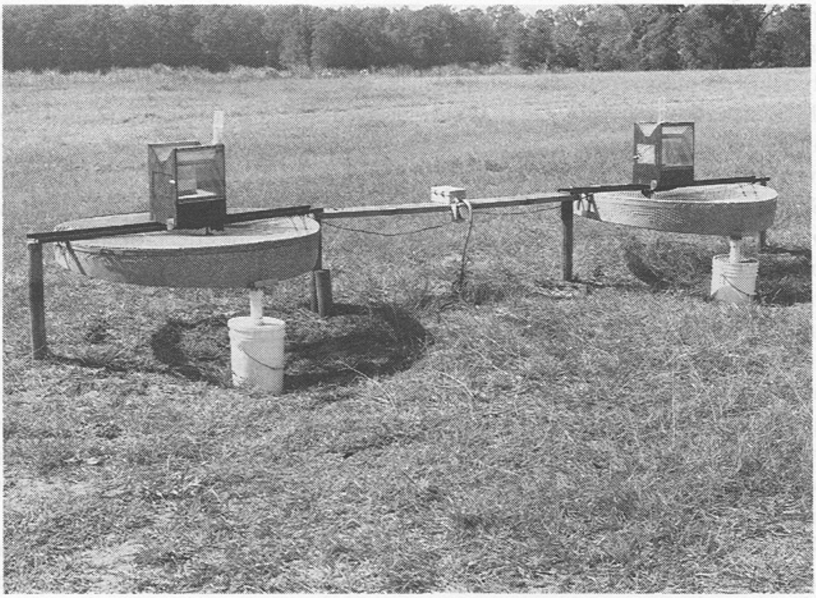

Figure 1. Standard trapping station used in Florida mole cricket project. Each station has two sound synthesizers, 3.5 m apart, that broadcast at 106 dB (at 15 cm) each evening. One synthesizer broadcasts the song of *Scapteriscus vicinus* and the other the song of *S. borellii*. Each is centered over a 1.5 m dia. mole cricket catcher (Walker, 1982) that slopes into a downspout leading to a bucket of sand. Each is covered by a wood-and-screen slit trap (Walker, 1989) that catches *Ormia depleta*, a phonotactic parasitoid fly. The time clock that controls the synthesizers is on the board between the yokes that support the traps and synthesizers.

research in Florida. Each station has two sound sources (one sound synthesizer for each of the mole cricket species it attracts) and four catching devices (each synthesizer has a large circular mole cricket catcher beneath and a smaller trap for parasitoid flies above). The two synthesizers are controlled by a single AC-powered timer that turns the sound on at sunset and off at sunrise.

Because they are easy to operate, reliable, and affordable, sound synthesizers have generally replaced the mechanical playback devices used as sound sources in early sound traps. An important advance in synthesizers has been the development of an economical "artificial cricket" by Bernie Mans [1929 Crisanto #226, Mountainview, CA 94040] under contract to University of Florida and with financial help from Clemson University. Utilizing a Motorola HC-11 microprocessor, this synthesizer can be programmed to produce any carrier frequency and modulate it at any pulse rate. (The pulse rate corresponds to the frequency at which the cricket cycles its wing movements during stridulation.) The resulting pulse train can be cut into chirps of any length at any compatible chirp rate. The Mans artificial cricket is powered by 12 v DC, either from an external battery or from a lines-powered DC source. It requires no external controller – a built-in photocell monitors light level and the unit turns on after a programmed light value has been achieved for a programmed duration; the unit then broadcasts for a programmed duration, and finally the unit ignores its photocell for a programmed duration. A 6-mil polyethylene bag, which transmits light and sound, protects the artificial cricket from rain. Since its development in 1989, more than 100 of these units have been used for mole cricket research in Florida, Georgia, and South Carolina.

Two other innovations in sound sources are noteworthy. Chukanov and Lapshin (1990) added a circuit to their synthesizer that used input from a thermistor to automatically adjust the pulse repetition rate to match the effect of temperature on naturally calling mole crickets. Ikeshoji and Ogawa (1988) increased catches by a mosquito sound trap by equipping it with a "board speaker," which emitted sound from a larger surface than previous traps.

Sound sources generally include amplifiers that permit the traps to broadcast well above the levels of the natural sounds they imitate. Tests on the effects of sound level on trap catch have generally shown that louder is better (e.g., Walker and Forrest, 1989). Forrest and Green (1991) developed a mathematical model of the effects of competing sound sources on the attraction of straight-travelling phonotactic insects that go directly to any attractive sound that exceeds some SPL (sound pressure level) threshold and to the louder of any two such sounds exceeding threshold. Their model agreed well with most empirical data from field studies of mole cricket phonotaxis. Nonetheless, for these two reasons, louder sound traps should not always be better: (1) Extremely loud sounds are expensive to produce and can damage unprotected human ears. (2) At some level the insect ear should saturate or fail.

Walker and Forrest (1989) attempted to find an upper limit for increasing sound trap catches of *Scapteriscus borellii* Giglio-Tos (a.k.a. *S. acletus* Rehn & Hebard) (Orthoptera: Gryllotalpidae) by increasing SPL. They failed, although they got a lesser benefit from a 12 dB increase from 116 dB to 128 dB than from a 12 dB increase to 106 or 118 dB (at 15 cm). Their loudest sound, 128 dB, had a sound pressure level approximately 79 times that of the loudest natural sounds of *S. borellii*.

Chukanov and Lapshin (1990) were first to report an upper limit to effective sound trap output. They used a sound synthesizer to drive four loudspeakers above a funnel trap for *Gryllotalpa* spp. mole crickets and produced a maximum SPL of 135 dB at 1 m. Mole crickets would approach but stop before reaching the funnel unless the SPL was reduced to 125 dB or below. At 1 m, assuming spherical spreading loss, Walker and Forrest's loudest call was 112 dB – i.e. Chukanov and Lapshin's loudest sound had an SPL 14 times as great and they got attraction to sounds that were 4.5 times as great. [If their sound level meter (not specified) read peak RMS pressure rather than averaging it over pulses, the difference between maximum sound levels used by the two teams would drop about 6 dB.]

Researchers using mosquito sound traps have increased their catches by adding swarm markers (Ikeshoji *et al.*, 1985) and by using chemicals and heat as supplemental attractants. For example, Kanda *et al.* (1987, 1988), in tests of sound traps for *Mansonia* and *Aedes* mosquitoes, showed that catches improved when dry ice and a guinea pig or hamster were added.

Catching devices must exploit the behavior of the target insects as they approach the acoustic bait. New catching devices were developed for field crickets (Campbell, 1990) and mole crickets (Chukanov and Lapshin, 1990). Both have funnels that can be entered by walking. The one for field crickets has a cover that restricts entry to a 1 cm gap around the periphery of the funnel – simulating a soil crevice occupied by a singing male. It has two speakers, one beneath the cover and one above. The trap for mole crickets has an open funnel with four horizontally aimed speakers mounted above.

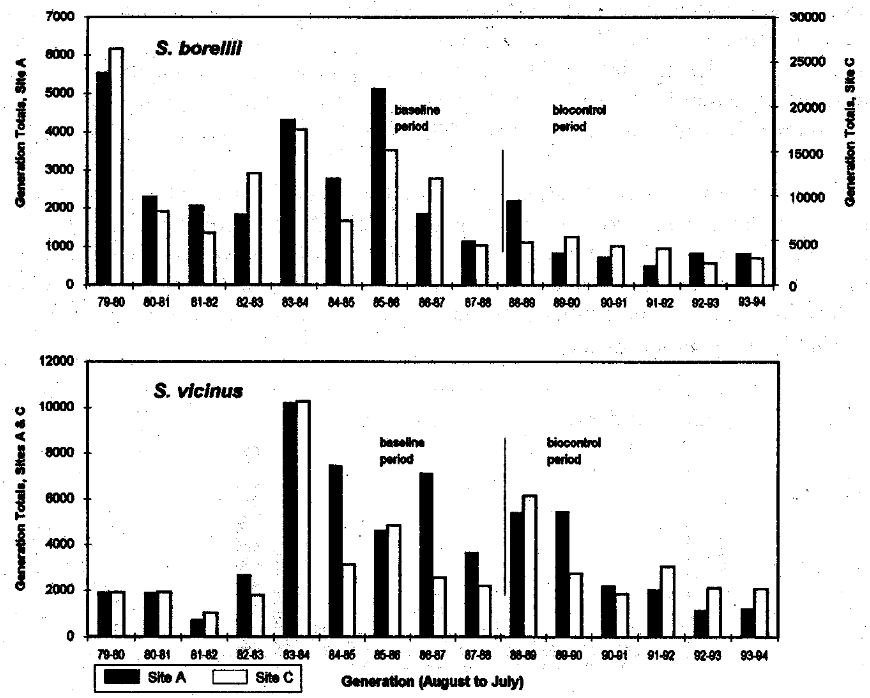

Figure 2. Population trends of two species of pest mole crickets (*Scapteriscus* spp.) at sites near Gainesville, Florida, as revealed by catches at standard stations (Fig. 1). Note that the trends for the two sites are similar, although the absolute numbers of *S. borellii* at site C average four times those at site A. The "biocontrol period" began upon the release of the biological control agents *O. depleta* (a tachinid fly) and *Steinernema scapterisci* (a nematode).

Uses of sound traps

Collecting living specimens. The most extensive use of sound-baited traps has been in conjunction with research on pest mole crickets in Florida and in their South American countries of origin. Collecting mole crickets with a shovel or by flooding is laborious and not very productive, nor can mole crickets be easily or quickly reared. However, tens, hundreds, or even thousands of mole crickets can be caught in one night with one sound trap (Walker, 1982). Mole crickets caught in sound traps have been used for studies of pesticides (Green *et al.*, 1984), chemical attractants and feeding stimulants (Kepner and Yu, 1987), sampling methods (Hudson and Saw, 1987; Hudson, 1989), ovipositional behavior (Forrest, 1986), and damage to specific cultivars (Walker and Ngo, 1982; Hudson, 1986). Furthermore, live specimens collected at sound traps have played important roles in developing and implementing biological control of mole crickets (Frank, 1994) – e.g., collecting and studying natural enemies in South America, rearing natural enemies in quarantine, and propagating enemies for inoculative releases.

Dispersing biocontrol agents. An innovative use of sound traps has been to speed the spread of a mole-cricket-killing nematode imported from Uruguay. Soil applications require large quantities of *Steinernema scapterisci* Nguyen & Smart, but with sound traps large numbers of mole crickets can be attracted to a modest quantity of nematodes and allowed to become infected. Once infected, the mole crickets can either be allowed to disperse naturally (by flight) or they can be retained and transported to wherever inoculum is desired (Frank and Smart, 1990; Frank, 1994; see also Ngo and Beck, 1982).

Field studies. Sound traps made possible a variety of field investigations of mole crickets in Florida, including studies of geographical distribution, population trends (Fig. 2), seasonal life cycles (Walker *et al.*, 1983), and dispersal flights (Walker and Fritz, 1983). More recently investigators in China (He *et al.*, 1989) and in the former USSR (Chukanov and Lapshin, 1990) used sound traps to reveal the diurnal timing of flights of *Gryllotalpa* spp. mole crickets.

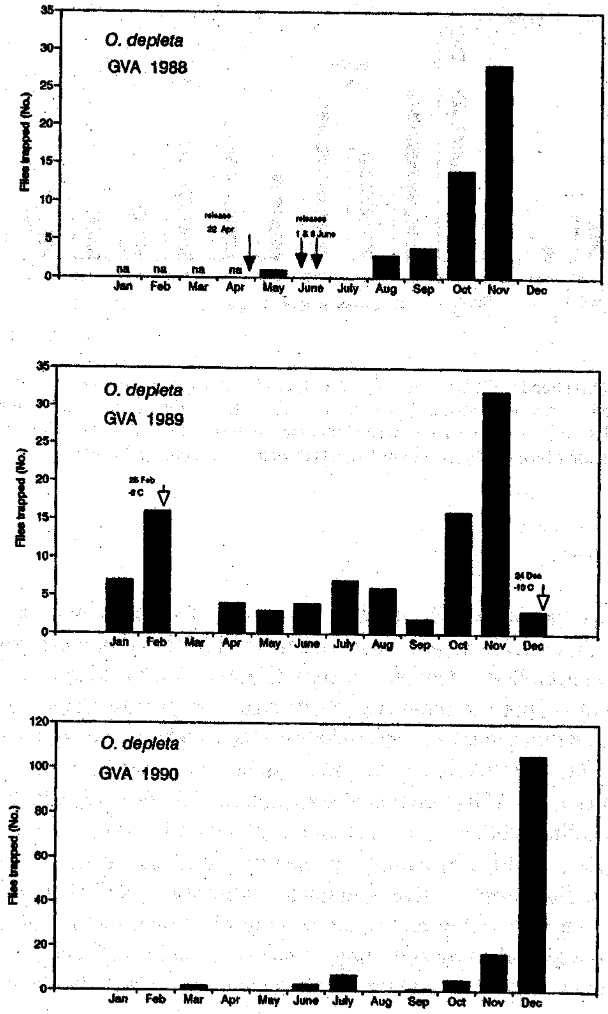

Figure 3. Establishment of *Ormia depleta* at site A near Gainesville, Florida, as revealed by catches at a standard station (Fig. 1). Note the change of scale in the Y-axis of the 1990 graph.

When sound traps were used for *Scapteriscus* spp. mole crickets in their homeland in South America, ormiine tachinid flies as well as mole crickets were attracted (Fowler, 1987). The flies were gravid females of *Ormia depleta* (Wiedemann) (Diptera: Tachinidae), which larviposit on or near calling mole crickets. The larvae enter the hemocoel and in about 10 days complete their development and kill their hosts. Sound traps were used to collect *O. depleta* for study and for shipment to Florida. When *O. depleta* was eventually released in Florida, sound traps were used to monitor its establishment (Fig. 3) and its geographic spread.

Sound traps have been used for field studies of other insects. Campbell and Shipp (1974, 1979) and Campbell (1990) used sound traps to monitor the activity of the field cricket *Teleogryllus commodus* (Walker) (Orthoptera: Gryllidae), an agricultural pest in Australia and New Zealand. Walker (1986, 1989) and Walker and Wineriter (1991) used sound traps to monitor seasonal occurrence of flights of two other field crickets, *Gryllus rubens* Scudder and *G. firmus* Scudder, and a phonotactic parasitoid, *Ormia ochracea* (Bigot) (Fig. 4). Walker (1993) subsequently used sound traps to compare the attraction of *O. ochracea* to the calls of various known and potential hosts. Leemingsawat (1989) baited traps with sound, a hamster, and dry ice to monitor anopheline mosquitoes in Thailand. Spangler (1984) showed that sticky traps baited with sounds of male lesser wax moths (*Achroia grisella* (Fabricius)) attracted virgin females and suggested that sound traps might be developed as a means of detecting lesser waxmoth populations within apiaries and bee equipment storage facilities.

Population suppression. Because sound traps catch large numbers of certain pest insects, sound traps might be successful in directly reducing populations of these insects. However, several considerations make this unlikely. Firstly, sound traps are costly to buy and to operate and are likely to remain so, given the physical and energetic requirements of producing loud sounds. Secondly, sound traps are short-range devices, requiring many units to cover moderate areas. Thirdly, the particular individuals attracted may not belong to the target population – e.g., they may be migrants rather than residents (Walker and Fritz, 1983) or flower-feeding males rather than blood-sucking, vectoring females

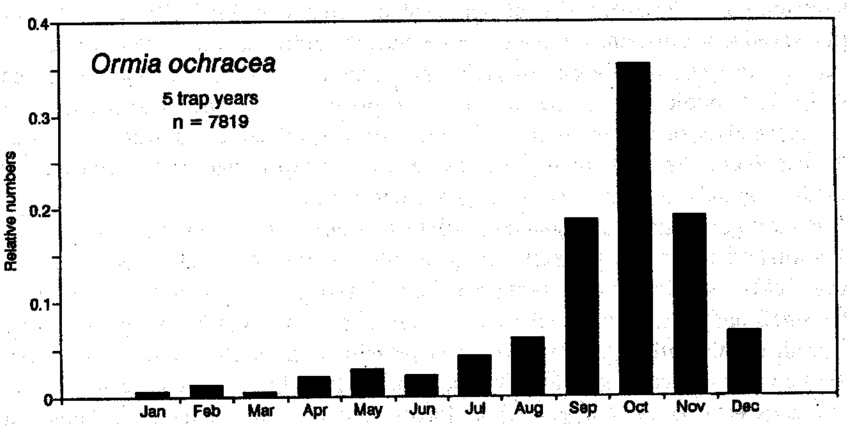

Figure 4. Seasonal occurrence of *Ormia ochracea* as determined by numbers trapped at synthesized calls of *Gryllus rubens* (a host) at two sites near Gainesville, Florida. Mean monthly relative numbers were calculated by averaging 5 relative numbers (one from each trap year), each of which was obtained by dividing the number caught in a trap that month by the annual total in that trap.

(Kanda *et al.*, 1987). Lastly, individuals may be attracted to the vicinity of the trap but not into the catching or killing area – e.g., most pest mole crickets attracted to a 1.5-m-diameter trap land outside the catching device (64% of *S. borellii* and 92% of *S. vicinus*; Matheny *et al.*, 1983).

Perhaps more promising is the use of sound traps to facilitate some other suppression technique. Their use in dispersing biological control agents was mentioned above. During the past decade, researchers in Japan and Thailand have worked to develop mosquito sound traps that can be used in suppressing mosquito populations. In early reports, the researchers sought to suppress populations by eliminating (Ogawa, 1988) or sterilizing males (Ikeshoji and Yap, 1987). More recently, their efforts have been directed toward attracting and reducing both sexes (Thongrungkiat, 1990; Ikeshoji and Yap, 1990; Kusakabe and Ikeshoji, 1990).

Repulsion

Attraction to sound has thus far failed as a means of suppressing insect populations. What are the possibilities that the opposite behavior, repulsion by sound, can be used to protect crops, livestock, or commodities from insect pests? As with attraction, the insects most likely to be repelled by a sound are those that are repelled by some natural sound and benefit from the avoidance. The only well-documented cases of this are a variety of flying insects that turn away, power dive to the ground, or make evasive flight maneuvers when exposed to real or simulated echolocating cries of insect-hunting bats. These include tympanate moths (Roeder and Treat, 1961), lacewings (Miller and Olesen, 1979), field crickets (Pollack and Hoy, 1989), locusts (Robert, 1989), and praying mantises (Yager *et al.*, 1990).

First to try putting bat avoidance to practical use were Belton and Kempster (1962). They broadcast a rotating beam of 50 kHz ultrasound over two plots of sweet corn and reduced infestation by European corn borer (*Ostrinia nubilalis* (Hübner)) by more than 50% compared to the control plots. Similarly, Payne and Shorey (1968) reduced oviposition of cabbage looper on lettuce and broccoli by 30 to 41% by playing pulsed ultrasound at 20 and 40 kHz. They also showed that areas receiving higher intensities had a greater reduction in oviposition (up to 66%) but concluded that this degree of reduction would not be economically significant in most cases. Agee (1969) and Agee and Webb (1968, 1969) studied the effects of pulsed ultrasound on bollworm (*Helicoverpa zea* (Boddie)) and European corn borer with a view toward protecting cotton and corn fields. They concluded that high intensities were required to repel, that sound shadows were difficult to avoid, and that most moths habituated rapidly.

Even if high-intensity ultrasound completely prevented oviposition by such pests as bollworm and corn borer, protecting large areas of relative low value – such as corn or cotton fields – would probably prove impractical. However, if the area to be protected were small and of high value, the cost of coverage would not be an obstacle. Such economic considerations have allowed the marketing of a variety of ultrasonic emitters as pest control devices – viz., to drive cockroaches from homes or businesses, to keep mosquitoes away, and to free pets of fleas. But these pests are little hunted by echolocating bats and have no auditory organs known to be tuned to ultrasound. Thus, there is no *a priori* reason for suspecting that these insects will be affected by ultrasound – except that insects and mice can be quickly killed by super-intense ultrasound (160 dB, ca 1 watt/cm^2) (Frings *et al.*, 1948). At any rate, when tested under controlled conditions, no commercial ultrasonic emitter has proved effective in repelling, mitigating, or controlling its target insects (e.g., Gold *et al.*, 1984; Schreck *et al.*, 1984; Koehler *et al.*, 1986; Dryden *et al.*, 1989; Hinkle *et al.*, 1990).

Detection of insect-generated sounds

In terms of monitoring insects by the sounds they generate, it is important to distinguish between *incidental* sounds, which are neutral or of negative value to the emitter, and *communication* sounds, which are acoustical displays that function to change the behavior of another animal, of the same or other species (Forrest, 1988). Incidental sounds include chewing and moving noises. Communication sounds include mating signals and warning signals. Incidental sounds are generally soft and hard to detect, whereas communication sounds are generally louder and, in some cases, difficult to ignore. Spangler (1985) described a device that detects the ultrasonic calling sounds of male lesser wax moths and demonstrated its usefulness in finding infestations. Forrest (1988) showed that using communication sounds to estimate populations – not just detect them – has many pitfalls that cannot be easily overcome.

The idea of detecting hidden insect infestations by their incidental sounds has a long history, but the microcomputer and other advances in electronics have given it new impetus. Its earliest application was to detect wood-boring insects in timbers (see Haskell, 1961), but the uses currently being pursued most vigorously are detection of insects in fruit and stored grain. Webb *et al.* (1988) developed a computerized system for acoustically detecting insect larvae in these commodities. The advantages of their system include its great sensitivity (the signal is amplified ca 90 dB), its specificity (most background noise is filtered out), and its sophisticated software (which reduces masses of data to a few pertinent statistics). Calkins and Webb (1988) describe the capability of this system to detect Caribbean fruit fly larvae (*Anastrepha suspensa* (Loew)) in grapefruit. This assay is of particular importance to Florida because its grapefruit are quarantined because of possible infestation by this fly, and large numbers of fruit must be cut and visually examined in order to establish that a shipment is free of larvae. Calkins and Webb showed that larvae could be detected acoustically even when so small that they were unlikely to be seen in cut fruit.

Using the system of Webb *et al.* (1988) with a detector that held a 1 liter sample of grain, Vick *et al.* (1988) demonstrated that lesser grain borer (*Rhyzopertha dominica* (Fabricius)), rice weevil (*Sitophilus oryzae* (Linnaeus)), and Angoumois grain moth (*Sitotroga cerealella* (Olivier)) feeding within kernels of rice, corn, or wheat could be detected by their feeding sounds. They illustrated the sensitivity of the method by detecting a last-instar rice weevil in a kernel in 1 liter of uninfested wheat even when the kernel was at maximum distance from the detector diaphragm. No matter how the grain is to be assayed for insects, removing samples from a mass of stored grain is difficult and labor intensive. Vick *et al.* (1991) put an acoustical sensor in a type of pitfall trap used to detect insects within stored grain. Their modification allows the trap to be left in place rather than needing to be periodically removed, examined, and reinserted. It also means that the monitoring can be continuous and automatic, making early detection much more likely.

Discussion and summary

Advances in electronics have increased the variety of ways in which sound can be detected, reproduced, analyzed, synthesized, amplified, and broadcast at the same time that the cost of these operations has decreased. This vastly increases the potential for using sound in monitoring and manipulating insects. The feeding of one tiny fly larva in a grapefruit or of a beetle larva in 1 of 22,500 kernels can now be reliably distinguished from background, and the acoustical bait of a sound trap can now be synthesized and controlled by a $12 microprocessor.

There is, however, an inherent limitation to acoustical methods: most insects do not hear well. That is to say they have no structures recognized as specialized detectors of airborne sound, nor are they known to respond to any natural airborne sound (including ultrasound). Thus far, acoustic methods have succeeded only when they depend on insect-generated sounds or exploit known behaviors in response to natural sounds.

Methods that take advantage of positive phonotaxis have had some noteworthy successes. Specifically, sound traps have greatly facilitated the study of mole crickets, field crickets, and their ormiine tachinid parasitoids. A loud broadcast of a naturally attractive sound brings in a catch many times larger than does the same sound at a natural level. Attraction to sound has yet to prove effective for population suppression, but research in Asia with mosquito populations is ongoing.

Methods that take advantage of repulsion by sounds have thus far been unsuccessful. Blanketing fields with simulated bat cries has reduced but not eliminated oviposition by tympanate moths. Ironically, ultrasonic emitters for the control of insects not known to hear ultrasound have been successfully marketed (or at least widely advertised) even though they are totally ineffective.

Methods relying on the detection of insect-generated sounds seem likely to exceed all others in their application and impact. Specifically, newly developed methods for acoustic detection of fly larvae in fruit and of assorted insect pests in stored grain promise to replace currently used methods that are more labor-intensive and less effective.

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