ECOLOGY AND BEHAVIOR

Eavesdropping on Insects Hidden in Soil and Interior Structures of Plants

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ABSTRACT Accelerometer, electret microphone, and piezoelectric disk acoustic systems were evaluated for their potential to detect hidden insect infestations in soil and interior structures of plants. Coleopteran grubs (the scarabaeids *Phyllophaga* spp. and *Cyclocephala* spp.) and the curculionids *Diaprepes abbreviatus* (L.) and *Otiorhynchus sulcatus* (F.) weighing 50–300 mg were detected easily in the laboratory and in the field except under extremely windy or noisy conditions. *Cephus cinctus* Norton (Hymenoptera: Cephidae) larvae weighing 1–12 mg could be detected in small pots of wheat in the laboratory by taking moderate precautions to eliminate background noise. Insect sounds could be distinguished from background noises by differences in frequency and temporal patterns, but insects of similarly sized species could not be distinguished easily from each other. Insect activity was highly variable among individuals and species, although *D. abbreviatus* grubs tended to be more active than those of *O. sulcatus.* Tests were done to compare acoustically predicted infestations with the contents of soil samples taken at recording sites. Under laboratory or ideal field conditions, active insects within ≈30 cm were identified with nearly 100% reliability. In field tests under adverse conditions, the reliability decreased to ≈75%. These results indicate that acoustic systems with vibration sensors have considerable potential as activity monitors in the laboratory and as field tools for rapid, nondestructive scouting and mapping of soil insect populations.

KEY WORDS *Cephus cinctus, Cyclocephala lurida, Diaprepes abbreviatus, Phyllophaga crinita, Otiorhynchus sulcatus,* subterranean

INSECTS THAT LIVE in soil or interior parts of plants are difficult to detect and monitor. The primary method for detection of soil insects in the field is a labor-intensive, visual search for damaged vegetation, followed by destructive digging, removal of the root mass, or water flushing of samples (e.g., Cobb and Mack 1989, Villani and Wright 1990). A few nondestructive detection techniques, including radiography (Villani and Wright 1988) and radioactive tracers (Frederickson and Lilly 1955), have been applied in small-scale laboratory studies. Acoustic techniques have been used to find insects in grain samples (Shuman et al. 1993, Mankin et al. 1997), grain bins (Hagstrum et al. 1996), and wood structures (Lemaster et al. 1997, Scheffrahn et al. 1997). In the laboratory, acoustic systems have been useful research tools for monitoring temporal patterns of hidden behavior (e.g., Shade et al. 1990). There is interest in developing acoustic methods for additional applications, primarily because these methods are nondestructive and have potential to decrease the costs and increase the speed of detecting insects in many different substrates.

The suitability of acoustic methods for detecting insects in soil, interior parts of plants, or other media depends on several biophysical factors. These include the signal to noise ratio of insect sounds (Michelsen and Nocke 1974), the distortion and attenuation of sounds as they travel through the medium (Michelsen et al. 1982, Markl 1983, Stewart and Zeigler 1984), similarities among frequencies and patterns of sounds made by other organisms (Stewart 1997), and the fraction of the measurement period during which signals are generated. Sound transmission in soil decreases exponentially with increasing distance from the source. Small changes in soil composition and packing can significantly affect the frequency dependence of sound transmission, but in general, attenuation increases as frequency increases (Liu and Nagel 1993).

Soil attenuates sound more strongly than grain, plant structures, or air at all frequencies, so the range over which an insect can be detected in soil is smaller. The attenuation coefficient of air increases from 8 × 10^{-5} dB cm^{-1} at 500 Hz (Beranek 1988) to 0.07 dB cm^{-1} at 120 kHz (Lawrence and Simmons 1982),

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where dB = 20 log10(P/Pref) is the signal level in decibel units (see also *Measurement Units* below), and P and Pref are actual and reference sound pressures, respectively. In grain, the attenuation coefficient increases from 0.02 dB cm^{-1} at 500 Hz to 0.06 dB cm^{-1} at 3 kHz (Hickling and Wei 1995). Markl (1968) measured sound attenuation coefficients in sand as high as 6 dB cm^{-1}. At these rates of attenuation, a weak signal ($<$30 dB above background) would become indistinct within ≈5 cm of the source. However, insect sounds with frequencies of $<$3 kHz have been detected through sandy soil over distances of 5–50 cm (Markl 1968, Brownell and Farley 1979), and they have been detected in plants and leaf mats over distances of up to 8 m (Stewart and Zeigler 1984).

We conducted tests with different acoustic sensors in different environments to extend the practical applicability of acoustic techniques for detection and monitoring of hidden insect infestations. The substrates tested included sand, clay, and potting soils at different levels of consolidation, and wheat plants. The sensors were chosen to represent a range of cost, portability, and ruggedness. They included accelerometers, piezoelectric disks, and a custom-developed soil-probe electret microphone system. The operating principles of these sensors which convert substrate and air vibrations into electrical signals are described in many handbooks and textbooks (e.g., Ikeda 1990).

The different insect species tested were chosen primarily for economic importance and partly for differences in size. *Cephus cinctus* Norton (Hymenoptera: Cephidae) is an important pest of wheat in the northern Great Plains. The larvae feed internally in the stems. *Cyclocephala lurida* (Bland) and *Phyllophaga crinita* (Burmeister) (Coleoptera: Scarabaeidae), and *Diaprepes abbreviatus* (L.) and *Otiorhynchus sulcatus* (F.) (Coleoptera: Curculionidae) are important soil insect pests. *Cyclocephala* spp. and *Phyllophaga* spp. are widely distributed and highly destructive pests of many cultivated crops including turfgrasses, forage grasses, corn, small grains, sugar cane, strawberries, potato tubers, and young nursery trees (Crocker et al. 1996). *D. abbreviatus* larvae feed on roots of a wide range of host plants (Simpson et al. 1996), and are of major concern to citrus growers in Florida (*Diaprepes* Task Force 1995). *Otiorhynchus* spp. feed on the roots of seedlings and potted plants (Nielsen et al. 1978) and are the most important insect pests in the Oregon nursery industry (Oregon Association of Nurserymen 1997).

Phyllophaga, *Otiorhynchus*, and other soil insects are often found in clumped distributions that reflect preferences for certain combinations of host plant, soil moisture and texture, and topography (Sweetman 1927; Guppy and Harcourt 1970, 1973). The detection and spatial targeting of these clumped populations is an important problem in integrated pest management (IPM) of mole crickets (Cobb and Lewis 1990) and Japanese beetles (Villani 1990, Dalthorp et al. 1999). Pest management programs for turfgrass frequently have failed because sampling to monitor insect pest populations was too time-consuming (Potter 1993). An acoustic method for rapid detection of soil insects would be a welcome tool for mapping pest populations in these programs.

Materials and Methods

Insects and Arenas in Laboratory Recordings. *Phyllophaga crinita* and *C. lurida* grubs weighing 100–300 mg were collected from turfgrass fields near Dallas, TX. They were maintained in regularly moistened sand in small plastic cups and fed sweet potato ad libitum. Recordings were made in a soil arena contained between two plastic sheets (0.16 by 30 cm square), 0.64 cm apart, or in 3.8-liter plastic containers filled with potting soil or builder's sand. Single or multiple recordings were obtained from 24 *P. crinita* and nine *C. lurida* grubs over a 2-yr period.

Otiorhynchus sulcatus grubs weighing 50–90 mg were obtained from a colony reared by James Fisher at the ARS Horticultural Crops Research Laboratory, Corvallis, OR. They were placed in four 0.5-liter containers with individual strawberry plants (*Fragaria* × *ananassa* Watson). Two containers held 10 and two held 5 grubs each.

Diaprepes abbreviatus grubs weighing 50–300 mg were obtained from a colony maintained at the U. S. Horticultural Research Laboratory, Orlando, FL (Lapointe and Shapiro 1999), and placed in pots (3.8, 19, or 76 liter) with small citrus root stock seedlings—either > 'Rough Lemon', *Citrus jambhiri* Lushington, or 'Carrizo' (citrange), *C. sinensis* (L.) Osbeck × *Poncirus trifoliata* (L.) Rafinesque-Schmaltz.

Multiple or single recordings were obtained from ≈150 grubs over a 2-yr period. *C. cinctus* larvae weighing 1–12 mg were obtained by exposing mated females to 'McNeal' spring wheat in the boot stage in a greenhouse cage. The wheat was fully headed when acoustic recordings were made 3 wk later. Single recordings were obtained from 18 larvae.

All laboratory recordings except for the tests with *C. cinctus* were made in a sound-insulated anechoic chamber (Mankin et al. 1996) to maintain low levels of background noise and to facilitate signal analysis. The *C. cinctus* recordings were made in a laboratory where all machinery and air conditioning equipment were temporarily turned off. It is possible to make useful recordings in any environment that does not have high levels of low-frequency background noise. The recording period was 180 s per sample unless stated otherwise.

Insects and Sites in Field Recordings. Sites in forage grass fields near Auburn University, Auburn, AL, and sites in Clarke County, AL, were acoustically monitored with a soil probe microphone or with accelerometers. Sites under small orange trees in citrus groves at the IFAS Citrus Research and Education Center, Lake Alfred, FL, were monitored with accelerometers. Visible organisms within a radius (30–50-cm) of the sensors were identified by digging up and sifting shovels (20 by 20 cm) of soil, or by pulling up a citrus tree and shaking the roots over a sifter. There were several hundred grubs and other insects in these recordings, including plant bugs (Miridae spp.), wireworms (Elateridae spp.), earthworms (Lumbricidae spp.), and millipedes (Diplopoda spp).

Piezoelectric Disk Sensor System. To record sounds from insects in the soil arena, a piezoelectric disk (MuRata Erie model PKM28-2AO, Smyrna, GA) was taped to the side of the plastic container, and the signal was conditioned with a Brüel and Kjær (B&K, Nærum, Denmark) model 2610 amplifier and a Krohn-Hite (Avon, MA) model 3100 bandpass filter (0.2–15 kHz). The signals were stored on a digital audio tape recorder (Panasonic model SV-255 DAT, Matsushita Electric, New York, NY, or TEAC model DA-P1, Montebello, CA) and monitored with headphones.

Soil Probe Microphone Sensor Systems. Field recordings were made with an electret probe microphone system custom-developed by Robert Hickling (Sonometrics, Huntington Woods, MI). The amplified signals were recorded on the TEAC digital recorder and monitored with headphones. At each test site, the probe was inserted ≈5 cm into a hole opened with a knife, and signals were recorded for 180 s.

Accelerometer Sensor Systems. In the tests to detect soil insects, steel spikes, 20 or 30 cm in length, were pushed into field soil or into 3.8-liter pots filled with potting soil or builders sand. An accelerometer (B&K model 4370) was attached magnetically to the spike head ≈5 cm above the ground surface. The signals were transmitted to a B&K model 2635 charge amplifier and band-passed filtered between 2–3,000 Hz. Signal storage and analysis procedures were the same as for the piezoelectric disk.

In the tests to detect *C. cinctus* in wheat, a B&K model 4371 accelerometer was attached to the plant by clamping it gently near the base of the stem with a screw-in attachment plate. Care was taken to keep the plant stable and upright. Signal amplification and recording procedures were the same as above.

Measurement Units. The magnitudes of acoustic signals are customarily measured as spectrum levels at specified frequencies (Beranek 1988). Absolute acoustic spectrum level magnitudes are expressed on a logarithmic scale referenced to the 20 μPa threshold of human hearing (i. e., dB = 20 log10(P/20 (Pa), where P is the signal pressure) (Mankin et al. 1996). Absolute vibration spectrum levels are measured in dB referenced to a threshold of 10^{-6} ms^{-2} (i. e., dB = 20 log10($A/10^{-6}$ ms^{-2}), where A is the acceleration) (Beranek and Ver 1992). In both measurement systems, sound pressure levels (SPL) are expressed as spectrum levels integrated (summed) over a specified frequency range (e.g., 0–3 kHz). The ratio of two signals (or when the signal is embedded in noise, the signal to noise ratio) is measured as the difference between two SPLs.

The accelerometer spectrum levels were calibrated against the 10^{-6} ms^{-2} thresholds by using B&K standards, and the accelerometer SPLs can be compared directly with values in the literature. However, the manufacturer of the electret and piezoelectric systems did not provide absolute calibrations against the 20-Pa acoustic threshold. To denote this difference, the figures showing measurements with these two systems are labeled in relative rather than absolute signal levels. The SPLs are listed in the figures primarily for comparative purposes, although we used an indirect calibration with microphone systems described in Mankin et al. (1996) to estimate the absolute dB levels.

Analysis of Recorded Signals. Custom-written software (Embree and Kimble 1991, Mankin 1994), and a personal computer system were used to perform spectral and temporal analyses. Before digitization, the recordings were bandpass-filtered between 0.1 and 10 kHz (KrohnBHite model 3100). The low-pass filter was needed to avoid aliasing (Embree and Kimble 1991) and the high-pass filter to eliminate low-frequency background noise. The filtered signals were amplified (B&K model 2610 amplifier) to range between ±5 V and digitized with a DAS-16 g A/D expansion board (Keithley Metrabyte, Taunton MA), usually at a 25-kHz sampling rate (25,000 amplitude samples/s). We digitized the *C. cinctus* recordings at a higher rate of 47.6. The digitized signals were processed by a custom-written subroutine (Mankin 1994). The subroutine identified signal pulses that exceeded a user-specified threshold. The threshold was set between the mean signal level and the mean background noise level. The beginning of the pulse was specified as the time when the signal level first passed threshold, and the end was specified where the signal remained below threshold for >4 ms. The subroutine placed the peak of each pulse at the center of a 4096–sample (160 ms) window, applied a Hamming filter, and calculated a power spectrum (e.g., Embree and Kimble 1991). Spectral averages of multiple sound pulses were constructed by calculating the power spectrum for each pulse, then averaging the spectrum levels at each frequency. The averaging process filtered out nonrecurring background noise and retained signal features that occurred in each pulse. For the *C. cinctus* recordings, we further reduced the amount of background noise in the spectrum by using a 520–sample (10 ms) window.

Spectral Profiles. Experience from listening to sound pulses in multiple recordings suggested that background noise often could be distinguished from insect sounds, and sometimes sounds made by different species could be distinguished from each other. Pulses recorded in the field tended to have a broader range of frequencies and temporal patterns than those recorded in the laboratory. To determine whether the perceived differences could be quantified by spectral analysis, we calculated spectral averages of multiple sound pulses from field sites where a single species had been recovered from a soil sample. These averages were used as profiles to match against individual sound pulses and possibly to identify the source. Profiles also were constructed from frequently occurring background sounds, including wind, airplanes, and trucks.

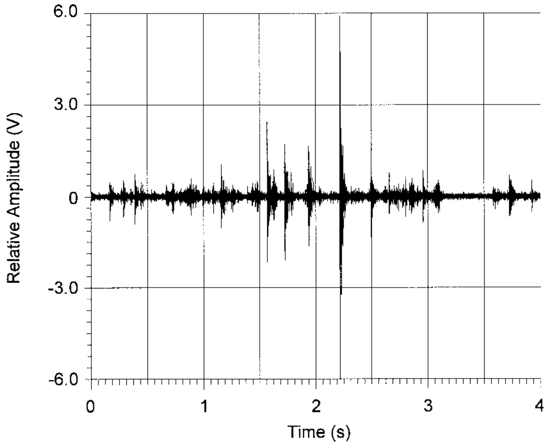

Fig. 1. Oscillogram of sounds made by a *P. crinita* grub in a 3.8-liter pot, recorded by an accelerometer.

Results and Discussion

General Properties of Insect Sound Pulses in Soil. Active *P. crinita, C. lurida, D. abbreviatus,* and *O. sulcatus* grubs produced sounds that could be detected by any of the tested microphone or accelerometer systems in small pots or the soil arena. The sounds of all four species were short pulses of irregular amplitude, usually without apparent pattern, examples of which are shown in the sample from a *P. crinita* recording in Fig. 1. Preliminary recordings indicated that there were large differences in the activity levels of individuals. A high variability in the rate and intensity of sound pulses also was observed in previous studies with stored-product insects (Shade et al. 1990, Pittendrigh et al. 1997, Mankin et al. 1999). Consequently, we did not attempt to distinguish among individuals or species by either sound rate or signal level.

Visual observations of 12 white grubs individually in the soil arena confirmed that sound pulses occurred during periods of movement and feeding activity. Visible movement of a grub anywhere in the arena was detected above background by a piezoelectric disk taped to one side and the signal-to-noise ratio was >20 dB between 0 and 3 kHz (e.g., Fig. 2). These observations indicate that piezoelectric disk systems have considerable potential for use as tools to monitor soil insect activity, similar to their previous uses with stored product insects (e.g., Mankin et al. 1999).

The grubs in this study were not necessarily active in every recording, and *D. abbreviatus* were more likely to be detected in random testing than *O. sulcatus.* In recordings from four 0.5-liter pots, a pot with 10 *O. sulcatus* grubs and one with five grubs had detectable activity in 12 recordings over a 3-d period. The other two pots had no detectable activity during the same period. By contrast, activity was detected over a 1-mo period in 23 of 27 recordings from nine 76-liter pots containing 20 *D. abbreviatus* each.

Comparisons of Accelerometer and Electret Microphone Measurements. Direct comparisons were made of signals recorded with the B&K model 4370 accelerometer and the electret microphone used in the Hickling soil-probe microphone system, the two used most often in the field tests. The accelerometer has constant sensitivity between 10 and 3,500 Hz, and a steadily increasing sensitivity from 3,500 Hz up to its resonant frequency near 16 kHz (Anonymous 1989). The electret has constant sensitivity up to ≈5 kHz, and a steadily decreasing sensitivity thereafter (e.g., Sessler 1998). The accelerometer has a higher overall sensitivity than the electret, but many of the signals we recorded were well within the electret's sensitivity

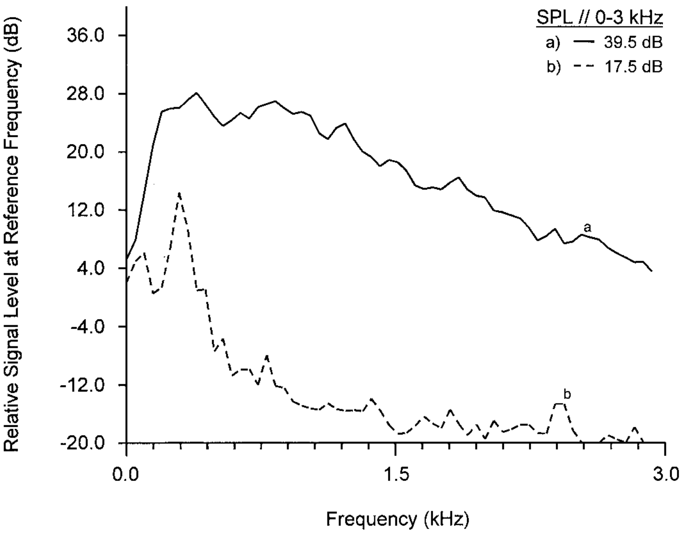

Fig. 2. 30-s average spectra of signals recorded from a piezoelectric disk taped to the side of the soil arena. (a) With *P. crinita* grub present. (b) Without a grub present.

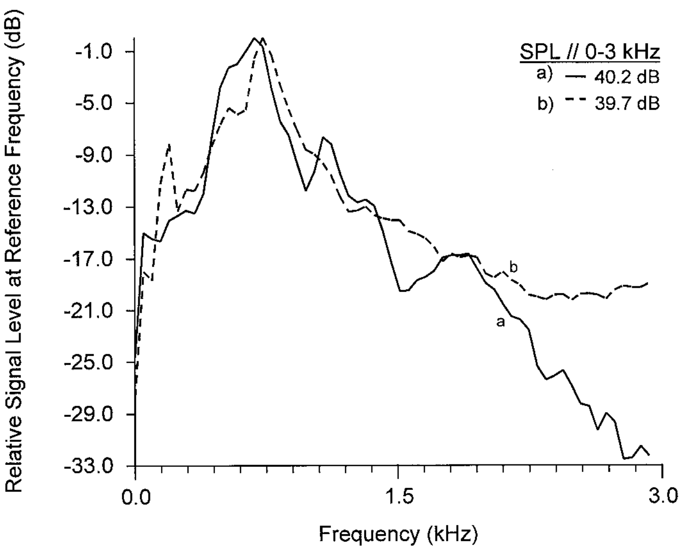

Fig. 3. Comparison of average spectra of sound pulses from a *P. crinita* grub detected simultaneously by (a) an electret microphone and (b) an accelerometer during a 30-s interval in a 3.8-liter pot.

range. Consequently, the spectral patterns of sound pulses detected simultaneously by the two sensors placed together in a 3.8-liter pot were similar up to ≈2 kHz (e.g., Fig. 3-4). Fig. 3 compares spectra of 37 pulses detected by each sensor from a *P. crinita* grub. Fig. 4 compares the spectra of 418 pulses detected by each sensor from *C. lurida* grubs. All of these spectra show a broad peak between 200 and 700 Hz.

***C. cinctus* Sound Pulses in Wheat.** *C. cinctus* larvae in wheat stems produced short, irregular, high-frequency sound pulses at a 44-dB sound pressure level with a broad peak near 2.7 kHz (Fig. 5). These are low-intensity signals, barely above the ≈20-dB background of a quiet wilderness environment and much lower than the ≈120-dB vibrations on the exterior of a small electric motor (Anonymous 1989). However, they are easily detectable because the background noise was low at frequencies of >300 Hz. The peak frequency near 2.7 kHz was higher than the peak for grubs in soil (Figs. 2- 4) but lower than the 3–8 kHz peak observed for *S. oryzae* larvae in grain (Mankin et al. 1996).

Sound Pulse Durations. The sounds produced by *C. cinctus, P. crinita, C. lurida, O. sulcatus,* and *D. abbreviatus* were similar in duration. An evenly divided sample of 100 pulses revealed no significant differences among species (duration = 2.87 ± 4.3 ms; F = 2.36; df = 4, 99; $P > 0.05$). The observed durations fall

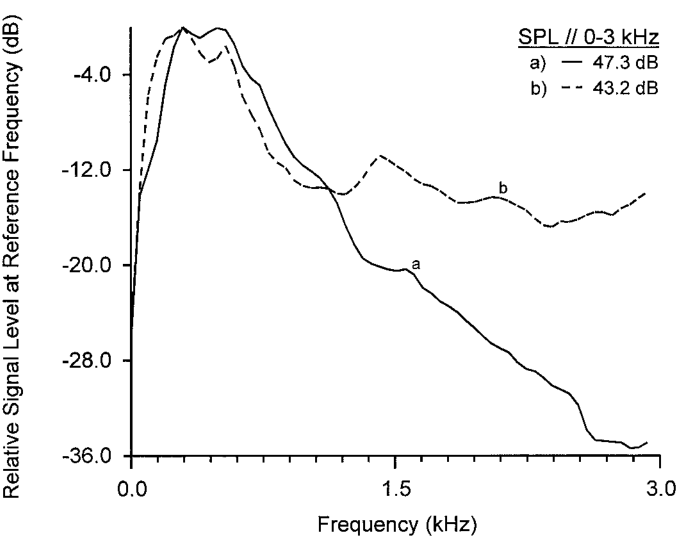

Fig. 4. Comparison of average spectra of sound pulses from nine *C. lurida* grubs detected simultaneously by (a) an electret microphone and (b) an accelerometer during a 30-s interval in a 3.8-liter pot.

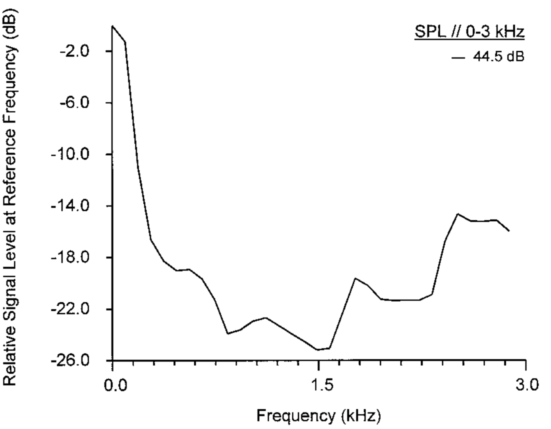

Fig. 5. Average spectrum of 51 sound pulses in a 27-s recording of a *C. cinctus* larva moving in a wheat stem.

well within the range of ≈0.1–10 ms observed for sounds made by *Sitophilus oryzae* (L.) larvae in grain (Mankin et al. 1996). Because of the similarity of pulse durations across the soil recordings, we did not attempt to use duration as a parameter to distinguish among individuals or species.

Comparisons of Spectra Across Multiple Recordings. The sound pulse spectra were expected to show considerable variation across recordings, partly because potting soil and builder's sand are unconsolidated materials whose sound-transmission characteristics are very sensitive to slight changes in the contacts between particles (Liu and Nagel 1993). Settling or slight movements in granular materials change the contacts between particles and alter the sound path. Variations in the sound transmission would cause the signals received by a sensor to differ across pots, even if the source produced identical signals. Fig. 6 shows an example of such variation. The two spectra are averages from recordings made at two different times in a 0.5-liter pot where 10 *O. sulcatus* larvae had been placed with a strawberry plant. The pulses in each separate recording are similar to each other, producing relatively smooth spectral averages. The average spectra in both recordings have broad peaks between 200 and 700 Hz, like those obtained with *P. crinita* and *C. lurida* (Figs. 2–4). However, the spectra differ considerably between 300 and 1,800 Hz on both a relative and an absolute scale. In this case, the between-recording differences are much greater than the within-recording differences. These large between-recording differences at high frequencies could be caused by settling, changes in the position of the sensor, or changes in the activity patterns or positions of the larvae. Similar differences occurred in field recordings (see below), except that high-frequency components appeared more frequently in the field than in the laboratory recordings.

Comparisons of Laboratory and Field Recordings. Sound pulses recorded in the field had the same low-frequency components as those in the laboratory pots, but many recordings also had high-frequency components that did not usually appear in laboratory recordings with the same species. In addition, background noise often contributed low-frequency noise of much higher intensity than occurs in the laboratory.

Such differences among frequency components are seen, for example, in the three profiles in Fig. 7. Each profile was obtained by combining spectra from 25–70 pulses in several recordings at different sites. The averages were calculated from groups of recordings where only one species was recovered in the soil sample. The average field-recorded *Phyllophaga* spp. spectrum has a peak near 1,900 Hz that is not readily apparent in the average laboratory spectra (e.g., Figs

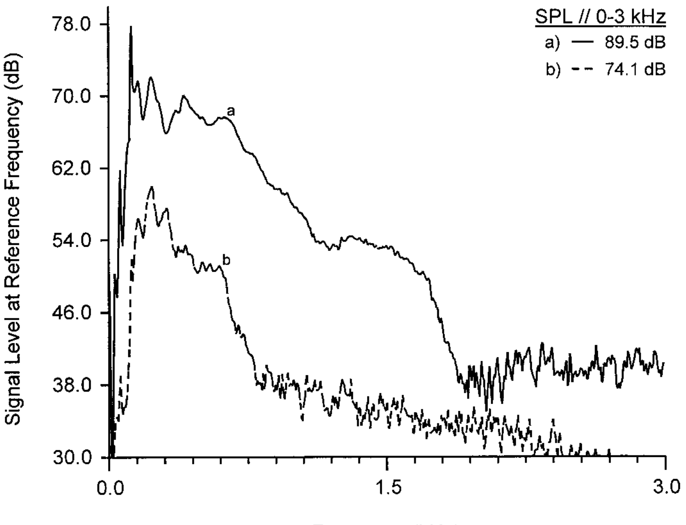

Fig. 6. Average spectra of signals recorded at two different times by an accelerometer in a 0.5-liter pot with 10 *O. sulcatus* grubs feeding on a strawberry plant. (a) Average of 17 sound pulses in a 60-s period. (b) Average of 20 pulses in a 60-s period.

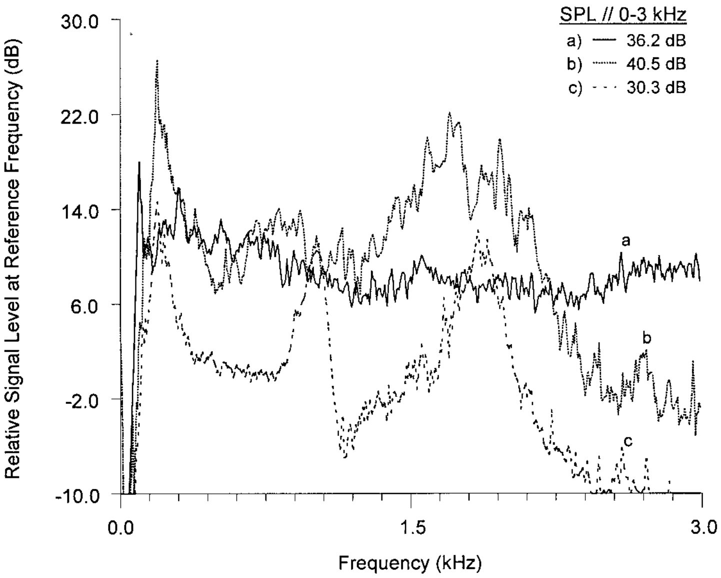

Fig. 7. Average spectra of sound pulses recorded from field sites with one insect species present. (a) *D. abbreviatus* (49 pulses). (b) *Phyllophaga* spp. (45 pulses). (c) plant bug (Heteroptera: Miridae) (89 pulses).

2 and 3). By contrast, the field-recorded *D. abbreviatus* spectrum has no distinctive peaks and is similar to the average spectrum from recordings of this insect in the laboratory.

Part of the differences among field and laboratory spectra may be caused by differences in soil composition and sound transmission paths. The *Phyllophaga* spp. recordings were made in hard ground with more structural rigidity and greater ability to carry high-frequency signals than the sand where these *D. abbreviatus* sound pulses were recorded, or the potting soil used in the laboratory. The plant bugs were on or near the soil surface and the sounds recorded from them could have been transmitted primarily through air. High-frequency sounds are transmitted better by air, grain, or plant structures (Fig. 5) than by soil. Whatever the cause, this spectral variability at high frequencies affected the choice of criteria for distinguishing between insect sound pulses and noise (see below).

Discrimination of Insect Sound Pulses from Background Noise. The spectral differences between background noises and insect sounds were greater than the differences among insect sounds alone, which may explain why a listener could distinguish insect sounds from background more easily than from other insect species. Fig. 8 shows the spectrum from a recording with a truck in the background. The spectral average of seventy 4,096-point segments of truck sound is easily distinguished from the profiles in Fig. 7 by an absence of peaks at frequencies of >300 Hz. Also, these types of sounds usually remained above background for periods of 10–100 s (depending on the time for the vehicle to pass out of the range of detection) in contrast to the 2.87-m mean duration of insect sounds. A computer subroutine was written to use these differences in discriminating insect sound pulses from noise. It discarded signals of long duration, D_{max} (usually >20 ms), and compared the spectra of individual sound pulses with sets of insect and background noise profiles like those shown in Figs. 7 and 8. The square of the difference between the pulse and profile spectrum level was calculated at each frequency in a specified range, F_{min} to F_{max}. The squared differences were summed and divided by the total number of differences to obtain the pulse's average deviation from each profile. Each pulse was classified according to which comparison produced the smallest average deviation. However, if any single spectrum level difference exceeded a specified single-level threshold, T_{sd}, or if the smallest average deviation exceeded a

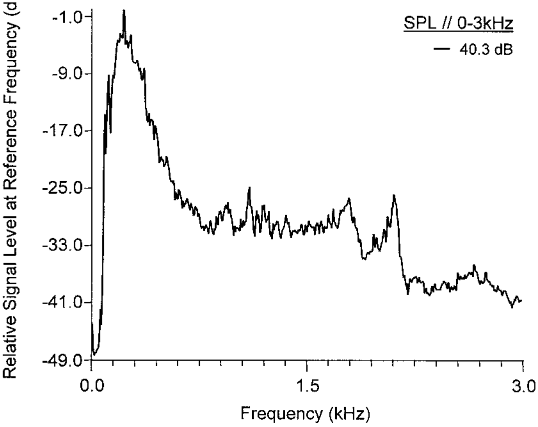

Fig. 8. Example spectrum of noise from a distant truck transmitted through soil to probe microphone (70 pulses).

specified average-deviation threshold, T_{ad}, the pulse was classified as noise. Thus, any pulse could be classified as one of the insect sounds, a specific background noise, or an unspecified noise.

This procedure has been tested in analyses of 169 recordings from a field in Clarke County, AL, containing *Polyphylla* and *Phyllophaga* spp., wireworms (Elateridae), and millipedes (Diplopoda), and in 70 recordings from a citrus grove at Lake Alfred, FL, containing *D. abbreviatus.* Sections of recordings were analyzed, and the subroutine's classifications of individual sound pulses were compared with those made by an experienced listener. The frequency ranges and threshold criteria were incrementally adjusted to improve the agreement between the subroutine and the experienced listener's classifications. For example, the initial frequency range was set at F_{min} = 300 Hz and F_{max} = 2,000 Hz to maximize the likelihood of classifying a pulse as an insect sound. This setting worked well in periods of low background noise, but some wind-noise pulses have medium-frequency components that caused them to be misclassified as insect sounds. In 18 recordings under windy conditions, resetting F_{min} from 300 to 1,200 Hz reduced the number of noise pulses misclassified as insect sounds, in one case by 100 pulses. However, an unknown number of true insect sounds that lacked strong high-frequency components probably were now misclassified as noise. The success of a computerized approach thus may depend on developing different sets of criteria for different background conditions (i.e., developing a decision system that combines acoustic data with information obtained by other methods).

Although the sources of individual sound pulses cannot be unequivocally identified, an experienced listener can make an overall prediction about whether the immediate area around a recording site is infested, and a computer can combine the classifications at a given site to predict whether infestation is present. The predictions then can be compared with the contents of soil samples. Examples of such comparisons are presented in the next section. The absolute range of detection is not certain because insect sounds vary in intensity, and they will attenuate at different rates in soils of different types and different levels of consolidation. However, our experience from examining the contents of soil samples and from tests with artificial noise sources suggests that, in general, insects can be detected over distances of 5–30 cm.

Identification of Infested Recording Sites. In an initial test of the computer classification system, the insect pulse and background noise counts were compared in Clarke County, AL, recordings at 20 sites with ± 3 organisms (grubs, earthworms, millipedes, plant bugs, and so on) to recordings at 10 sites where no visible organisms were recovered from the soil samples. Four insect profiles were used in the test, including the average *Phyllophaga*, *D. abbreviatus*, and Miridae spectra shown in Fig. 7, and an additional, 40-pulse average spectrum from a second recording where only *Phyllophaga* spp. were recovered. Two noise profiles were used, the truck spectrum in Fig. 8, and an 82-pulse average from a recording where an airplane flew overhead. The analysis settings were: F_{min} = 300 Hz, F_{max} = 2,000 Hz, D_{max} = 25 ms, T_{sd} = 30 dB, and T_{ad} = 2.5 dB. The distributions of the numbers of pulses per minute in the two groups overlapped, but 75% of the sites with ≥ 3 organisms and only 40% of the sites with no organisms had >8 pulses per minute classified as insect sound pulses. Thus, the computer classification system already can identify infested sites at levels better than chance by using the criterion that an insect is predicted at the site if >8 pulses per minute match at least one of the insect profiles. The method remains under development, and we expect that further improvements will be made by devising techniques to reduce the number of noise pulses misclassified as insect pulses.

Several small-scale tests have been done to estimate the accuracy of an experienced listener in predicting whether a particular site has been infested. The results are somewhat dependent on background noise level, but they suggest a high level of predictability. In one test in a grove near Lake Alfred, FL, 11 small orange trees were tested and pulled. The experienced listener predicted that five contained insects. One or more *D. abbreviatus* were found under four of those trees. The listener predicted that the other six were not infested, and no visible organisms were observed. In a second test in a grove near Plymouth, FL, six trees were tested. Five of the trees had been artificially infested with three *D. abbreviatus* larvae each. All five infested trees were correctly identified. In the laboratory tests with *C. cinctus,* sounds were detected in 18 stems of ≈50 examined on different occasions. A larva was found in each of these stems, and no larvae were found in stems without detectable sounds. In general, it is easier to identify insects in a quiet laboratory setting than in the field. The success of such tests and experience with long-term monitoring in the laboratory suggest that acoustic monitoring by an experienced observer may be particularly useful for monitoring the efficacy of control treatments (i.e., for determining whether previously occurring activity has ceased).

Practical Applications of Acoustic Technology for Detection of Soil Insects. The impetus for developing an acoustic system to detect insects in soil was a lack of inexpensive, nondestructive methods that could be adapted for field use. The systems described in this report are portable and have been rugged enough to survive a variety of southeastern United States temperature and moisture extremes. The sensors detect insects over distances of 10–30 cm, depending on the structure and type of soil and the peak frequencies of the sound pulses. We adopted a standard listening period of 180 s, but insect sounds often could be detected within 15–20 s. Consequently, the listening period could be reduced in field situations where sampling time is an important consideration. There are no major obstacles to their use in monitoring behavioral activity of soil insects or internal feeders like *C. cinctus* in a quiet laboratory environment. The major limitation for field usage, at present, is uncertainty in the interpretation of the signals detected by the acoustic sensors. Some of this uncertainty is caused by background noise, by variability of sound transmission at different recording sites, by temporal and environmental variability of insect behavioral activity, and by lack of experience in integrating acoustic data with other kinds of information known about insects and other organisms at a particular recording site.

In this respect, the future use of acoustics for detection of insects in soil and other observationally inaccessible habitats may be analogous to its current use in engineering for the prediction of machinery failure (e.g., Pusey 1999). A number of nondestructive acoustic tests have been developed that are not perfectly reliable by themselves but are useful diagnostic tools when combined with information obtained by other techniques. The method is sufficiently robust that it has rapidly developed into an important diagnostic tool as practitioners have developed improved methods of integrating the acoustic data with other information.

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