

Geophone Detection of Subterranean Termite and Ant Activity

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ABSTRACT A geophone system was used to monitor activity of subterranean termites and ants in a desert environment with low vibration noise. Examples of geophone signals were recorded from a colony of *Rhytidoponera taurus* (Forel), a colony of *Camponotus denticulatus* Kirby, and a termite colony (undetermined *Drepanotermes* sp.) under attack by ants from a nearby *C. denticulatus* colony. The geophone recordings were compared with signals recorded from accelerometers in a citrus grove containing *Solenopsis invicta* Buren workers. Because of their small size, all of these insects produce relatively weak sounds. Several different types of insect-generated sounds were identified in the geophone recordings, including high-frequency ticks produced by *R. taurus* and *C. denticulatus*, and patterned bursts of head bangs produced by *Drepanotermes*. The *S. invicta* produced bursts of ticks with three different stridulation frequencies, possibly produced by three different-sized workers. Overall, both systems performed well in enabling identification of high-frequency or patterned pulses. The geophone was more sensitive than the accelerometer to low-frequency signals, but low-frequency insect sound pulses are more difficult to distinguish from background noises than high-frequency pulses. The low cost of multiple-geophone systems may facilitate development of future applications for wide-area subterranean insect monitoring in quiet environments.

KEY WORDS acoustics, soil insects, geophone, accelerometer, stridulation

ACOUSTIC TECHNOLOGIES THAT HAVE BEEN applied successfully for detection of subterranean insects primarily use accelerometers or acoustic sensors to detect soil-borne vibrations (Mankin et al. 2000). Geophones, however, are the most commonly used sensors for detection of seismic activity because of their high sensitivity to <0.3-kHz signals that travel long distances underground (Lay and Wallace 1995, Paine 2003). Geophones also have been used to study communication and foraging behavior in subterranean vertebrates (Narins et al. 1997) and communication in *Gryllotalpa major* (Sassure) (Hill and Shadley 1997).

Accelerometers are preferred over geophones for most soil insect detection applications because they have better sensitivities and lower noise floors at frequencies >0.5 kHz (Sleepe and Engler 1991), where subterranean insect sounds typically have their greatest energy (Mankin et al. 2000). However, because the weak, low-frequency sounds produced by individual ants (Spangler 1967) or small groups of ants and other low-weight insects (Mankin et al. 2000, 2001) have a significant fraction of energy below 0.5 kHz, geophones might be able to detect them over greater distances than accelerometers in some applications.

Weak insect-produced sounds are less likely to be masked by background noises in desert areas and other locations that are remote from urban sources of vibration background noise; consequently, geophones would be expected to have utility for detecting and monitoring small insects in such areas.

A recently initiated study of *Notoryctes* marsupial moles (Benshemesh and Johnson 2003, Dennis 2004) provided an opportunity to use geophones to monitor subterranean insect activity in desert areas near Alice Springs, Australia. Recordings were obtained from *Rhytidoponera taurus* (Forel), *Camponotus denticulatus* Kirby, and a colony of *Drepanotermes* termites under attack by workers from a nearby *C. denticulatus* colony. To relate the geophone measurements to previous research with acoustic sensors (Mankin and Lapointe 2003, Zhang et al. 2003) and termites (Mankin et al. 2002), we compared insect and background noise signals obtained from geophones with signals obtained by accelerometers in recordings from similarly sized insects in comparable environments. The accelerometer recordings were obtained from probes inserted into soil near *Solenopsis invicta* Buren workers in a citrus grove in Florida. *S. invicta* workers are polymorphic, with a two-fold range in length and a 20-fold range in weight (Tschinkel et al. 2003). In general, major workers have head widths >0.75 mm and weights >0.7 mg, whereas minor workers have smaller head widths and weights (Tschinkel et al. 2003). The *Drepanotermes* workers observed at the surface of the mound during the ant attack seemed similar in size to *S. invicta* minor workers. The *R. taurus*

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and *C. denticulatus* workers observed after mound disturbance were approximately the size of *S. invicta* major workers.

Like many ant species (Hölldobler and Wilson 1990, Pavan et al. 1997), *S. invicta* have a stridulatory organ and can produce low-intensity, <40-dB sound pressure level (Hickling and Brown 2000), bursts of stridulatory ticks (Spangler 1967). Although localized groups of 10 or more active *S. invicta* usually produce sounds that can be detected by an accelerometer (Mankin et al. 2001), individual workers are well below the 8–13-mg minimum weights of insects that are reliably detected over distances of 5–10 cm in soil (Mankin and Fisher 2002, Mankin et al. 2000). If the sensitivities of the geophones and accelerometers are comparable, we expected that sounds made by individual ants would be difficult for the geophone to detect, but a colony would be easily detectable. Similarly, we expected that individual termites would not be detectable except for head banging, which can be loud enough to be detected by humans without electronic amplification (Howse 1970, Connétable et al. 1999).

Materials and Methods

Geophone Measurements. The geophones (model GS-32CT, Geo Space LP, Houston, TX) were supplied by the Australian National Seismic Imaging Resource, Australian National University, Canberra, Australia. In these tests the four geophones in the sensor unit were taped together and used as a single sensor inserted into the soil (henceforth referred to as the geophone probe). The GS-32CT has a sensitivity of $0.197 \text{ V cm}^{-1}\text{s}^{-1}$ between 10 and 500 Hz and an extended bandwidth of lower sensitivity at higher frequencies (www.geospace.com/industry2.shtml). Custom-built high-gain amplifiers were supplied by Biotelemetry Tracking Australia (Adelaide, Australia).

To monitor insect activity, the geophone probe was inserted directly near an opening in an insect colony at three different sites near the campus of the Arid Zone Research Institute in Alice Springs, Northern Territory, Australia. The signal output was monitored by headphones and recorded on a portable Walkman model MZ-R700 (Sony Corp., New York, NY). A recording of ≈ 6 min was obtained from a colony of *R. taurus*. A recording of ≈ 12 min was obtained from a colony of *C. denticulatus*, and a 20-min recording was obtained from a termite colony (undetermined *Drepanotermes* sp.) under attack by ants from a nearby *C. denticulatus* colony. Additional tests were done to consider the sensitivity of the geophone to footsteps, tapping or scratching of leaves on nearby plants, dropping of pebbles, and other background noises.

Accelerometer Measurements. The acoustic system included an accelerometer (model 4370, Brüel and Kjær [B&K], Nærum, Denmark) with a sensitivity of 10 pC/ms^{-2} between 0 and 12 kHz, a charge amplifier (B&K model 2635) with $0\text{--}10^4$ gain, a digital audio tape recorder (model DA-PI, TEAC, Montebello, CA), and headphones. The accelerometer was magnetically attached to a 30-cm steel probe inserted into

the soil. Recordings were obtained from two separate sites near colonies of *S. invicta* during an acoustic survey of an experimental citrus grove at the University of Florida Institute of Food and Agricultural Sciences Indian River Research and Education Center, Ft. Pierce, FL (Mankin and Lapointe 2003). Excavations of these sites after the recordings indicated that *S. invicta* were the only sound-producing organisms. Background noise recordings were obtained from two adjacent sites where no sound-producing organisms were recovered after excavation.

Signal Analysis. The accelerometer signals were band-pass filtered between 0.1 and 9.6 kHz and digitized as .wav files at a sampling rate of 48 kHz with a CSL speech analysis system (model 4300B, Kay Elemetrics Corp., Lincoln Park, NJ). The geophone signals were processed similarly except that the background noise levels were 2–10-fold higher than in the accelerometer recordings. Head bangs and other insect-generated sounds could be monitored by headphones without filtering, but it was necessary to increase the low-pass filter frequency from 0.1 to 0.24 kHz to enable reliable detection by the digital signal processing systems that were used to visualize, audibilize, and analyze the signals. Three different software programs were used in different aspects of these analyses: the DAVIS insect sound analysis system (Mankin et al. 2000, 2001), the CSL speech analysis system, and Sound Ruler (Sourceforge, Austin, TX).

The magnitudes of the vibrations were measured on a logarithmic, decibel (dB) scale referenced to the frequency range between 0.3 and 6 kHz. For the accelerometer, absolute vibration levels were referenced to 10^{-6} ms^{-2} acceleration (Beranek and Ver 1992), i.e., $\text{dB} = 20 \log_{10}(A/10^{-6} \text{ ms}^{-2})$, where A was the acceleration at a specified frequency. Similarly, relative vibration levels were referenced to the maximal acceleration, A_{max} , in the 0.3–6-kHz reference range, i.e., $\text{dB} = 20 \log_{10}(A/A_{max})$. Because the geophone measured velocity instead of acceleration (Hill and Shadley 1997), the magnitudes of the absolute vibration levels were measured in $\text{dB} = 20 \log_{10}(V/10^{-9} \text{ ms}^{-1})$ where V was the velocity at a specified frequency, and relative vibration levels were referenced to the maximum velocity, V_{max} , in the 0.3–6 kHz reference range, i.e., $\text{dB} = 20 \log_{10}(V/V_{max})$.

Initially, each recording was screened by headphone to identify and exclude periods where vehicle noise, bird calls, or electronic interference precluded signal processing of insect-produced sounds. The termite mound recording was further screened to identify bursts of head banging and periods where both termites and ants were active. The accelerometer records were screened to identify sections with high levels of *S. invicta* activity. Mean background spectra were calculated by averaging vibration levels in consecutive 10-ms segments of noise-free periods. The vibration levels were averaged at each discrete Fourier harmonic frequency between 0.3 and six kHz. In this experiment with a 48-kHz sampling rate and a 512-point spectrum, i.e., a 93.75-Hz harmonic fre-

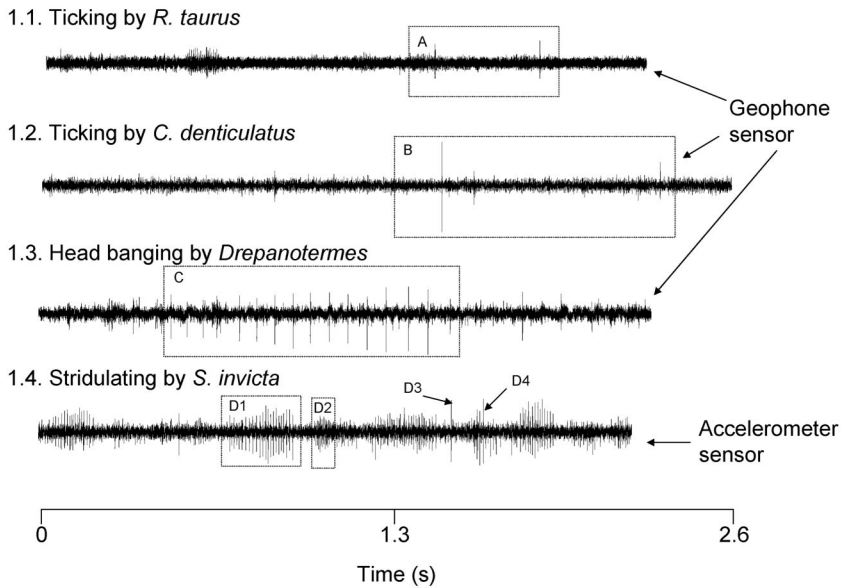


Fig. 1. Oscillograms of signals recorded from ant and termite mounds with a geophone (1.1–1.3) or an accelerometer (1.4). Insets show two ticks recorded from mound with *R. taurus* (1.1.A); three ticks recorded from mound with *C. denticulatus* (1.2.B); 16 head bangs recorded from a mound of *Drepanotermes* under attack by *C. denticulatus* (1.3.C); and two series of slow and rapid stridulations (1.4.D1 and D2, respectively); and two isolated ticks (1.4.D3 and D4) recorded near a mound with *S. invicta*. To enable visual identification of insect sounds, signals below 0.24 kHz were filtered in oscillograms 1.1–0.3 and signals below 0.1 kHz in 1.4.

quency difference, the discrete frequencies were 375, 468.75, . . . , 6000 Hz (Mankin 1994).

Insect Sound-Pulse Analysis. To characterize the insect signals in each file, the DAVIS software conducted a sample by sample search for pulses whose peaks exceeded a user-adjustable minimum threshold. The insects in this experiment produced sound pulses 0.1–1 ms in duration. A power spectrum was calculated for a 2-ms (96-sample) section of signal centered on the peak of each pulse (Mankin et al. 2000). Mean spectral profiles were calculated as averages of vibration levels for groups of pulses that were independently verified as produced by a particular insect species. Verification of insects at the geophone sites was obtained by observing and identifying insects emerging after the probe was inserted into a mound and by monitoring of the recorded signals by headphones. The insects in the accelerometer recordings were identified by pulling up the tree and examining the contents of the rootball and the disturbed area.

In the recording at the *Drepanotermes* mound, listeners identified multiple periods that seemed to contain concurrent termite and ant activity. These periods were analyzed by least-squares matching of the spectrum of each individual pulse to the mean spectral profiles for head bangs and ticks in the frequency range between 0.3 and 6 kHz (Mankin et al. 2000). The time, profile classification, and peak amplitude of each pulse were saved in a data file to enable subsequent analysis of temporal patterns of head-banging and ant ticks.

Results and Discussion

Analysis of Detected Sounds. Several distinctive signals were identified as possible insect sounds at each recording site, including high-frequency ticks in the mounds containing *R. taurus* (Fig. 1.1.A) and *C. denticulatus* (Fig. 1.2.B), and head-banging bursts in the mound with *Drepanotermes* (Fig. 1.3.C). Individual ticks (Fig. 1.4.D3 and D4) and stridulation bursts (Fig. 1.4.D1 and D2) were detected by the accelerometer in areas containing *S. invicta*.

The identifiable insect sounds in these recordings were of low amplitude but detectable because they occurred within a context of low-to-moderate background noise. The background noise was primarily from wind gusts, aboveground insects and vertebrates, and engines. Most such noise, except for bird and insect song, contained predominantly low frequencies that could be filtered out to highlight the higher frequency insect sounds. Figure 2 compares the background noise levels in two 10-s accelerometer recordings (Fig. 2A and B) and a 7-s geophone recording (Fig. 2C) of periods without identified insect sounds. The recording from the accelerometer and geophone in low-noise conditions (Figs. 2A and C) contained no distinct signals identifiable by ear, but the geophone had a 10-dB or higher response than the accelerometer to the background signals between 0.3 and 1.5 kHz because of its high sensitivity to vibrations in this spectral region. The second accelerometer recording (Fig. 2B) included a 4-s wind gust as an example of a distinct, but filterable background noise. The gust con-

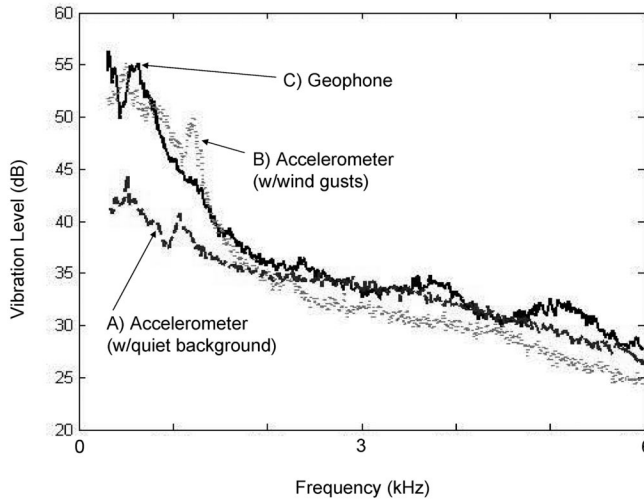


Fig. 2. Mean spectra of background noise in periods with no insect sounds. The geophone (2.C) and one accelerometer profile (2.A) were obtained during quiet periods with no listener-identified sounds. The second accelerometer profile (2.B) was obtained during a period that contained a wind burst.

tributed a 15-dB signal between 0.3 and 1.5 kHz, but all of the background noise had dropped ≈ 20 dB from peak levels within frequencies above 1.8 kHz. Because the insect sounds under study rarely exceeded 40–50 dB (Mankin et al. 2000), field studies become progressively more difficult to perform if background signals are more than approximately twofold (5–8 dB) above the levels seen in Fig. 2B and C.

The two small peaks in the geophone spectrum at 3.75 and 5 kHz may reflect a slight nonuniformity in the spectral sensitivity of the geophone at these frequencies. Geophones are not expected to have uniform sensitivity to frequencies above 1 kHz (Lay and Wallace 1995).

Spectral Profiles of Insect Sounds. Spectral analysis of noise-free sections of recordings from different sites confirmed initial listener observations that the ticks detected at the *C. denticulatus* mound had spectral patterns distinct from the spectra of head bangs detected at the *Drepanotermes* mound as well as from the spectra of ticks from the *R. taurus* mound (Fig. 3), with relatively higher signal levels at frequencies between 3 and 6 kHz. The profile of *R. taurus* ticks shown in Fig. 3 was an average of eight ticks recorded during a 2-s period from the *R. taurus* mound. The profile of *C. denticulatus* was averaged from 10 ticks recorded in a 2.5-s period from the *C. denticulatus* mound. The *Drepanotermes* profile in Fig. 3 was averaged from 28

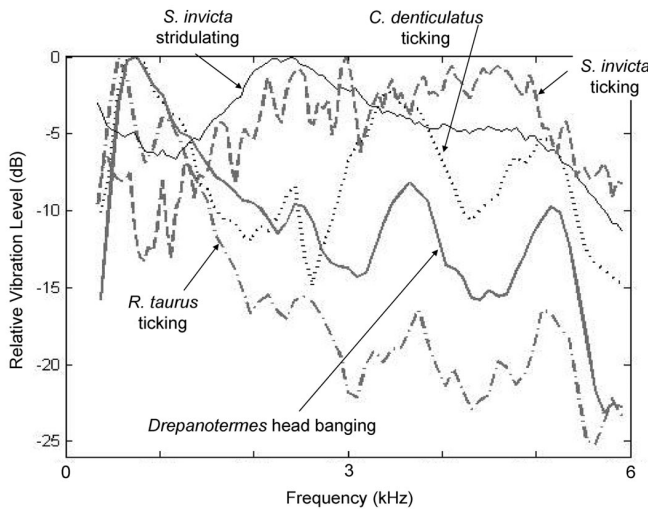


Fig. 3. Examples of spectral profiles of *Drepanotermes* head bangs, *C. denticulatus* and *R. taurus* ticks, and patterned (stridulation) and unpatterned (ticking) sounds by *S. invicta*.

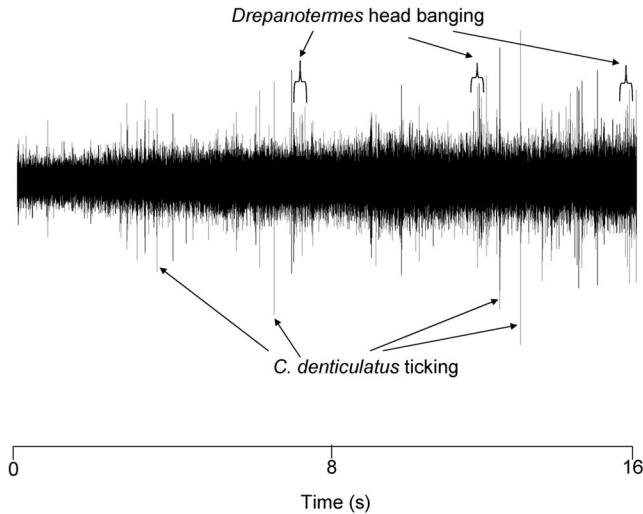


Fig. 4. Example of a period of concurrent head banging by *Drepanotermes* and ticking by *C. denticulatus* (head bangs and ticks were identified by least-squares matching of individual pulse spectra to profiles in Fig. 3).

head bangs in a 2.2-s period during which no *C. denticulatus* ticks were detected by headphone monitoring. Groups of ticks that matched the *C. denticulatus* profile also occurred at the *Drepanotermes* mound attacked by *C. denticulatus* workers. However, the head bangs could be easily distinguished from the *C. denticulatus* ticks using either the headphones or the spectral profiles because the ticks were ≈ 5 dB louder than the *Drepanotermes* head bangs at frequencies above three kHz, and the head bangs occurred in distinct temporal patterns (see below).

The profile of individual *S. invicta* ticks in Fig. 3 was obtained as an average of six ticks in an 8.5-s period, and the *S. invicta* stridulation profile was an average of 448 ticks in a 2.3-s period. No spectral differences were observed among ticks that occurred at different stridulation rates in this study (Fig. 1.4.D1 and .D2), but the possibility that such differences exist is not ruled out. The *S. invicta* stridulation profile overlapped with the profile of individual *S. invicta* ticks at frequencies between 1.7 and 5 kHz. In addition, the *S. invicta* profile was similar to the spectrum obtained by Spangler (1967) for stridulations produced by *Pogonomyrmex occidentalis* (Cresson) which suggests that all of these ticks may have been generated by a similar mechanism, i.e., by rubbing a ridge on the gaster across a scraper on the postpetiole (Spangler 1967).

The functional significance of the ticks is not well established, but like head banging (Howse 1970), the stridulatory bursts are considered possibly to be alarm or recruitment signals (Markl 1965, Tschuch and Brothers 1999), mechanical facilitation of cutting (Roces and Hölldobler 1996), or soil movement (Spangler 1974). The current capability of geophone and accelerometer technology to detect such signals provides considerable opportunity for future studies to help clarify the behavioral significance of these sounds.

Periods of Concurrent Ticks and Head Bangs. The oscillogram in Fig. 4 shows an example from one of

three different periods where ticks and head bangs occurred concurrently in the 20-min recording from the *Drepanotermes* mound. The ticks and head bangs marked in Fig. 4 were identified by the DAVIS signal analysis program, which classified each individual pulse against the *C. denticulatus* and *Drepanotermes* profiles using a least-squares matching procedure. The ticks and head bangs also were distinguishable to the ear, as the ticks were higher in frequency. The head banging was not continuous, and no head banging was detected after the *C. denticulatus* withdrew from the mound, ≈ 5 min before the end of the recording.

Temporal Patterns of Head Banging and Stridulation. The head-bang and stridulation bursts occurred in distinctive patterns that facilitated their identification by headphone monitoring and signal processing software. The head-bang pulses had similar amplitudes and interpulse intervals within each of 18 separate bursts identified in the 20-min recording at the *Drepanotermes* mound. The mean head-bang frequency varied within a narrow range, with a mean of 18.28 ± 0.76 head bangs/s (minimum 12.6/s and maximum 27.1/s). The mean interval between head bang pulses was 0.0562 ± 0.00183 s. In contrast, the distribution of the numbers of head bangs across bursts had relatively greater variability, ranging from two to 18 head bangs per burst in the recorded sample (Fig. 5).

The head-banging recordings were obtained as a test of detection techniques rather than as a study of termite behavior. A more complete study of the tropical termites, *Pseudacanthotermes militaris* (Hagen) and *Pseudacanthotermes spiniger* (Sjöstedt) by Conétable et al. (1999) reported head-bang frequencies similar to those found here for *Drepanotermes* (14.12 ± 2.74 head bangs/s for *P. militaris* and 18.99 ± 4.11 head bangs/s for *P. spiniger*).

Like the head bang bursts in the *Drepanotermes* recordings, the stridulation bursts produced by *S. invicta* workers were easily recognized because the ticks

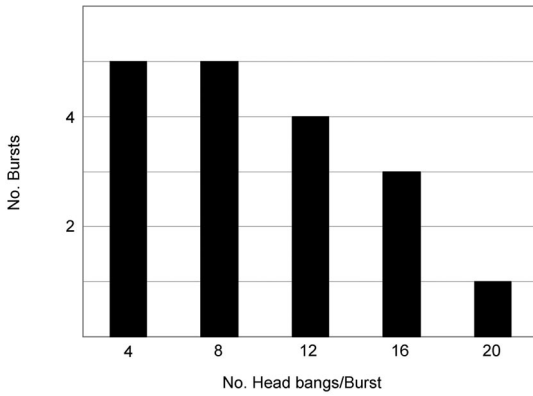


Fig. 5. Numbers of head bangs in 18 separate bursts in a 20-min recording from *Drepanotermes* mound during an attack by a nearby *C. denticulatus* colony.

within individual bursts were spaced at relatively constant intervals (Fig. 1.4.D1 and 1.4.D2). The numbers of ticks in different *S. invicta* stridulation bursts were distributed differently than head bangs in *Drepanotermes* bursts, however, possibly because of differences in the sound production mechanisms. The numbers of ticks per burst clustered into three distinct groups (Fig. 6). Cluster A in Fig. 6 contains a group of 14 bursts from both accelerometer recording sites ranging >4 and <16 ticks/burst, with a mean of 8.6 ticks/burst and a mean total duration of 54.0 ms per burst. Cluster B contains a group of seven bursts from both sites ranging >16 and <28 ticks/burst, with a mean of 23.4 ticks/burst and a mean total duration of 142.3 ms per burst. Cluster C contains a group of four bursts from both sites ranging >48 and <60 ticks/burst, with a mean of 54 ticks/burst and a mean total duration of 228.5 ms per burst. These results are consistent with a hypothesis (Spangler 1967) that each stridulating ant has moved its gaster through a “chirp” of 8–9 ticks

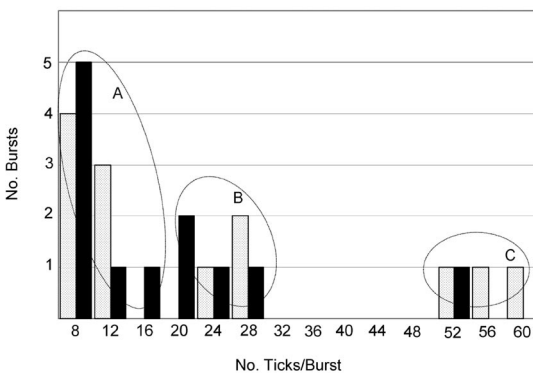


Fig. 6. Distribution of numbers of ticks in 25 bursts of *S. invicta* stridulations recorded from two different sites (hatched and solid bars, respectively). Insets A–C designate groupings of tick counts that may be reflective of differences in the numbers of separate movements of the gaster across the scraper.

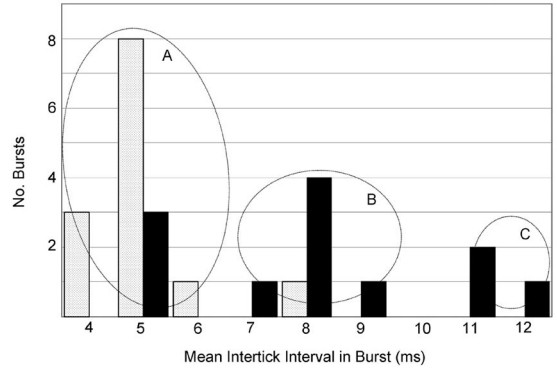


Fig. 7. Distribution of intertick intervals in 25 bursts of *S. invicta* stridulations recorded from two different sites (hatched and solid bars, respectively). Insets A–C designate groupings of mean intertick intervals that may be reflective of differences in the sizes of different workers.

(6A), three consecutive chirps (6B), or six consecutive chirps (6C).

The intertick intervals and the mean tick frequencies noticeably varied among bursts (Fig. 7). Inspection of the distribution peaks in Fig. 7 suggests that there were three different clusterings of intertick intervals in the two recordings. Cluster A contains a group of 15 bursts from both sites with intertick intervals >3 and <6 ms and a mean of 4.43 ms (225.7 ticks/s). Cluster B contains a group of seven bursts from both sites with intertick intervals >6 and <9 ms and a mean of 7.58 ms (131.9 ticks/s). Cluster C contains a group of three bursts with intertick intervals >10 and <12 ms and a mean of 10.6 ms (94.3 ticks/s). These bursts were detected at only one of the sites. The observed distribution of intertick intervals across bursts and recording sites could result from differences in the sizes and consequently of differences in the distances between ridges on the stridulation organs of different workers. Tschinkel et al. (2003) noted that there was a range of different sizes and classified major workers as those with head widths >0.75 mm and weights >0.7 mg, and minor workers as those with head widths <0.75 mm and weights <0.7 mg. If each worker moved its gaster across the post-petiole scraper at approximately the same rate, the mean tick frequency would be higher for minor workers than major workers, and in-between for intermediate-sized workers. Under such a hypothesis, the probe at one site possibly was inserted near minor and intermediate-sized *S. invicta* workers, and at the other site was inserted near minor, intermediate-sized, and major workers. The hypothesis cannot be confirmed from counts of the excavated ants in this field study because it would be difficult to determine which of the ≈50 excavated ants at each site had been stridulating.

Detection of Weak Insect Sounds. The sound pulse analyses in these tests suggest trade-offs that ultimately determine whether weak sounds produced by small insects can be detected with geophone or vibration sensors in a field test. The geophone is highly

sensitive to signals of <0.5 kHz frequency, but the nature and magnitude of the background noise typically makes it difficult to discriminate whether brief sound pulses at these frequencies are because of insects or other causes. Consequently, it is not necessarily possible to take full advantage of this higher level of sensitivity. The pulses that were identifiable as insect sounds in this study were either short, high frequency sounds with distinctive spectra, or they occurred in patterns of similar amplitude and frequency. Additional detection studies with geophones may reveal other insect sounds that occur in patterns which can be detected from long distances or in high noise backgrounds, but individual, isolated insect sounds are difficult to detect over long distances with either a geophone or an accelerometer. However, the low cost and widespread availability of geophones may facilitate development of future applications in entomological field studies.

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