Acoustic Detection of Termite Infestations in Urban Trees

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ABSTRACT A portable, low-frequency acoustic system was used to detect termite infestations in urban trees. The likelihood of infestation was rated independently by a computer program and an experienced listener that distinguished insect sounds from background noises. Because soil is a good insulator, termite sounds could be detected easily underneath infested trees, despite the presence of high urban background noise. Termite sounds could be detected also in trunks, but background noise often made it difficult to identify termite signals unambiguously. High likelihoods of termite infestation were predicted at four live oak (*Quercus virginiana* Mill, Fagacae), two loblolly pine (*Pinus taeda* L., Pinacae), and two baldcypress (*Taxodium distichum* Rich. Pinacae) trees that wood-baited traps had identified as infested with *Coptotermes formosanus* Shiraki. Infestations also were predicted at two pine trees with confirmed recoveries of *Reticulitermes flavipes* (Kollar). Low likelihoods of infestation were predicted in four oak trees where no termites were found. Additional tests were conducted in anechoic environments to determine the range of acoustic detectability and the feasibility of acoustically estimating termite population levels. There was a significant regression between the activity rate and the number of termites present in a wood trap block, with a minimum detectable number of ≈50 workers per liter of wood. The success of these field tests suggests that currently available acoustic systems have considerable potential to detect and monitor hidden infestations of termites in urban trees and around building perimeters in addition to their present uses to detect and monitor termite infestations in buildings.

KEY WORDS *Reticulitermes flavipes, Reticulitermes virginicus, Coptotermes formosanus,* acoustics

NUMEROUS EFFORTS TO develop techniques for detecting hidden termite infestations have produced only a few successful alternatives to traditional visual inspection methods (Lewis 1997). Notable alternatives include ground-based monitoring devices (Su and Scheffrahn 1986, Su 1994) and sensors that detect acoustic emissions of termites in wood (Fujii et al. 1990, Lewis and Lemaster 1991, Noguchi et al. 1991, Robbins et al. 1991). Acoustic emission sensors are successful because they are nondestructive and operate at high frequencies (>40 kHz) where there is negligible background noise to interfere with detection and interpretation of insect sounds (Lewis and Lemaster 1991, Robbins et al. 1991). In addition, to providing evidence of termite presence, acoustic emission systems have been applied as research tools to estimate termite population levels (Fujii et al. 1990, Lewis and Lemaster 1991, Scheffrahn et al. 1993).

Acoustic emission systems have been used primarily for detection of termites in wood but there is also an obvious need to detect termites in soil around building perimeters and trees (Osbrink et al. 1999, Kramer 2001). Unfortunately, soil has a much larger coefficient of sound attenuation than air or wood and the coefficient of attenuation increases rapidly with frequency (Liu and Nagel 1993). This attenuation reduces the detection range of acoustic emission to ≈2–5 cm in soil (for background, see Markl 1968, Mankin et al. 2000).

The range of acoustic detection is much greater at frequencies <10 kHz, and low-frequency accelerometers have been used to detect insect larvae over 1–2 m in grain (Hickling and Wei 1995; Shuman et al. 1993, 1997) and 10–30 cm in soil (Mankin et al. 2000, 2001; Brandhorst-Hubbard et al. 2001). The sound-insulating properties of soil help reduce interference from background noise; consequently, modern signal processing techniques can be used to distinguish insect sounds from background noises with good reliability in typical field environments (Mankin et al. 2000, 2001). To consider whether such techniques could be applied also in a relatively noisier urban environment, we conducted a series of exploratory studies to detect termites acoustically under different laboratory and urban noise conditions. Three different termite species were monitored: *Reticulitermes flavipes* (Kollar), *R. virginicus* Banks, and *Coptotermes formosanus* Shiraki (Rhinotermitidae).

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Materials and Methods

Outdoor Urban Recording Sites. Recordings were obtained from eight live oak (*Quercus virginiana* Mill, Fagacae) (coded O1-O8), four loblolly pine (*Pinus taeda* L., Pinacae) (P1-P4), and two baldcypress (*Taxodium distichum* Rich. Pinacae) (C1-C2) trees at the USDA ARS Southern Regional Research Center, New Orleans, LA. Osbrink et al. (1999) identified these trees as infested or uninfested in a 6-mo survey with 500 ground monitor stakes just before the acoustic study. Multiple recordings (see *Acoustic Measurements*) were taken from four 30-cm spikes inserted ≈15 cm from the base of each tree, with one recording site in each compass quadrant. At several trees, additional recordings were made where major roots branched near the surface. Additional recordings also were made from screws inserted at multiple locations ≈30 cm above ground on the trunk of pine P3 and along radial lines extending from the base of oak O1, both heavily infested with *C. formosanus.*

Insects and Arenas for Laboratory Recordings. Preliminary studies were conducted in the laboratory to assess the detection range of accelerometer sensors in wood and determine an approximate relationship between sound rate and termite population. *R. virginicus* workers were collected by W. Osbrink in a wooded area on the University of Florida campus, Gainesville, FL. Two groups of 50, 100, and 300 workers were placed into cavities chiseled near the ends of separate pine planks (5 by 10 by 240 cm). The control was an identical plank without workers. Sounds were recorded and monitored with headphones over a 5-d period by using an accelerometer (see *Acoustic Measurements*) attached to one of six 8-cm nails spaced at 30-cm intervals. The measurements were performed in an anechoic chamber (Mankin et al. 1996) to eliminate background noise.

A study to measure a relationship between sound rate and numbers of termites was conducted with *R. flavipes* workers collected by F. Oi from bucket traps (Su and Scheffrahn 1986) monitored at the University of Florida. Three groups of 100, 500, and 1000 workers were placed in (≈150 g, 8 by 8 by 15-cm) wooden trap blocks placed in sand in unused, 3.8-liter paint cans. Three uninfested blocks were used as controls. An 8-cm nail was inserted into each block before infestation to serve as an attachment point for the accelerometer. Tests were conducted with individual cans set in a small anechoic chamber. The blocks were moistened at regular intervals and the lids were closed except during recording sessions. Sounds were recorded and monitored with headphones one or two times daily on weekdays for 30 d. Temperatures were maintained at 20–24°C. The live termites in each block were counted at the end of testing.

Acoustic Measurements. The acoustic system included an accelerometer (Brüel and Kjær [B&K] Nærum, Denmark), sensitivity 10 pC/ms^{-2}, weight 54 g), a charge amplifier (B&K model 2635), and a digital audio tape recorder. The accelerometer was attached magnetically to a 30-cm spike or an 8- or 15-cm screw inserted at the recording site. A >180-s period was recorded and monitored with headphones in each site. The recorded signals were digitized and analyzed with a digital signal processing system (Mankin 1994; Mankin et al. 2000, 2001) that provided computer assessment of activity and distinguished termite sounds from background noise.

Moving and feeding termites generated short (0.5–5 ms) broadband pulses that could be distinguished from nontermite noises by analysis of differences in how the signal amplitude varied over time or frequency (viewed, respectively, in an oscillogram or a spectrum). The amplitude of general background noise usually varied slowly, with a time scale of seconds or minutes rather than milliseconds. Consequently, much of the noise could be filtered by discarding signals with amplitudes below a noise threshold set ≈20% of the root mean square in a 0.3-s interval containing the signal (Mankin et al. 2001). Signals that exceeded threshold for durations >200 ms were discarded also. When the signal processing subroutine identified a short pulse that exceeded threshold, it calculated a frequency spectrum for a 3-m segment of signal centered at the peak of the pulse. The spectrum was compared with previously characterized profiles of termite and background sounds (see below) and the most closely matched profile identified it as a termite or a noise pulse (Mankin et al. 2001). Samples of termite and noise pulses are available at cmave.usda.ufl.edu/≈rmankin/soundlibrary.html.

Sound Pulse Spectral Profiles. To distinguish termite sounds from background noises and compare among sounds produced by different termite species, spectral profiles were constructed from relatively noise-free sections of recorded signals from verified infestations. A profile of *C. formosanus* sounds was derived from 928 pulses recorded from oak (O1) where termites were excavated at the recording site. A profile of *R. flavipes* sounds was derived from 256 pulses recorded from pine (P1) where *R. flavipes* were excavated. A profile of *R. virginicus* sounds was derived from 55 pulses recorded from an artificially infested plank in the laboratory. A background noise profile was derived from 267 pulses obtained from an uninfested site at the Southern Regional Research Center during a period of high background noise. Vibration level, a measure of the signal energy (Parsons and Griffin 1988), was measured as acceleration in decibels (dB) on a relative scale between specified frequencies (e.g., dB//0.5–3.5 kHz, Mankin et al. 2000). It should be noted that the termite pulses matched the profile of any termite species more closely than they matched the background profile (Results). Consequently, any of the three termite profiles could have been used successfully to distinguish the termite sounds from background noise.

Sound Activity Rate Analyses. The pulse activity rate was calculated as the number of pulses matching a specified termite template divided by the analysis period for each data file. Spatial distributions of sound activity were plotted using ArcView GIS 3.2 (Environmental Systems Research Institute, Redlands, CA).

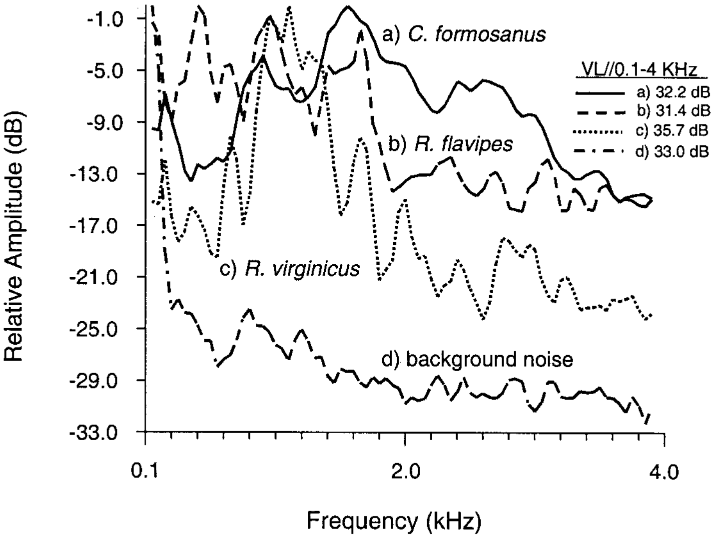

Fig. 1. Mean spectra (profiles) of signals recorded by accelerometer from independently verified sources: *C. formosanus* (a), *R. flavipes* (b), *R. virginicus* (c), and urban background noise (d). Vibration levels (VL) between 0.1 and four kHz are set on a relative scale.

For the study of sound activity in relation to numbers of termites in wood blocks, the number alive on a given day was estimated by interpolating between initial number and the final number recovered, assuming a constant rate of mortality. Regression analysis for termite number on termite pulse activity rate was performed using PROC GLM (SAS Institute 1988).

Listener Rating of Infestation Likelihood. Listeners were trained in laboratory and field exercises to distinguish termite sound pulses from sounds of other invertebrates, vehicles, wind and leaf-flutter, birds, dogs, and other vertebrates. Training included listening and recording practice with independently verified sources of termite sounds, and practice with generating and interpreting equipment-related background noise. Training also included visual comparisons of spectral and temporal patterns obtained from a computer library of insect sound pulses and background noises (see examples at cmave.usda.ufl.edu/~rmankin/soundlibrary.html). Listeners subjectively rated the likelihood of termite infestation after recording and listening at each test site. The rating scale was as follows: low, no subterranean sounds or only a few faint termite sound pulses, easily lost in the noise background; and high, frequent termite sound pulses with a high signal level, easily distinguished from background. Trees were considered potentially infested if one or more sites under the tree received a high rating.

Results and Discussion

Acoustic Identification of Termite Infestations. Sound pulses matching independently verified termite spectral profiles (Fig. 1) could be detected easily in

Table 1. Termite sound activity at trees rated by listener at high likelihood of infestation, sorted in order of mean activity rate

Tree no.[a]	Mean activity rate (termite pulses/s) at site in quadrant				Mean activity rate at tree (termite pulses/s)	Identified species[b]
	South	East	West	North		
P3[c]	76.8	90.8	17.0[d]	14.8	49.9	*C. formosanus*
O1[e]	58.6	30.4	60.9	22.8	43.2	*C. formosanus*
C1	0	0	0	74.0[d]	18.5	*C. formosanus*
O4	0	13.8[d]	30.2	0	11.0	*C. formosanus*
O2	0	0	40.0[d]	0	10.0	*C. formosanus*
P1	0	18.7	0	20.1	9.7	*R. flavipes*
O3	31.5	0	0	0	7.9	*C. formosanus*
C2	0	0	21.5[d]	0	5.4	*C. formosanus*
P4	0	7.5[d]	0	0	1.9	*C. formosanus*
P2	0	0	0	4.7	1.2	*R. flavipes*
	Mean activity rate (termite pulses/s)					
	56.0 ± 12	32.2 ± 14	34.0 ± 10	27.4 ± 4		

[a] O, oak; P, pine; C, cypress. Trees O5–O8 had no discernable termite pulse activity and were rated by the listener and the computer at low likelihood of infestation. Mean activity rate at tree is mean of recordings from four quadrants.

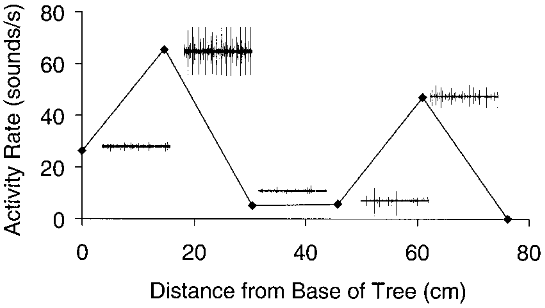

Fig. 2. Distribution of *C. formosanus* sound activity recorded at different distances from base of tree O1: insets show 1-s samples of signals recorded at each site.

recordings at eight trees (Table 1) identified as infested by Osbrink et al. (1999). No termite sound pulses were detected at four oaks where no infestations had been found. Previous studies of *C. formosanus* sounds (Scheffrahn et al. 1993) indicate that the largest, and possibly all of the easily detectable sounds are caused by feeding activity.

The termite sound pulses had short durations and high frequencies (see below) that listeners could recognize easily to distinguish them from urban background noise. Listeners correctly rated the likelihood of infestation as low for the four uninfested oaks and high for the other eight trees. At the two most heavily infested trees, P3 and O1, loud, frequent pulses were heard at one or more sites in all four quadrants.

The amplitude and rate of sounds varied widely among sites, even at a single tree. Examples of this variation are seen in the oscillogram insets in Fig. 2, which shows activity rates at increasing distances along a radius from the base of Tree O1. In each 1-s oscillogram, the heights of the vertical lines indicate the sound pulse amplitude and the thickness of the horizontal line across the center is a measure of the mean amplitude of background noise. A magnified 0.05-s section of *C. formosanus* signal in Fig. 3 shows an example of the fine structure of the signal. The two horizontal lines at ±100 mV indicate the noise threshold used by the signal analysis program to identify candidate termite pulses (see *Acoustic Measurements* above). The oscillograms in Figs. 2 and 3 include relatively noise-free sections of signal. All of the above-threshold sounds seen in Fig. 3 were identified as termite pulses by the computer program.

In Fig. 2, signal-to-noise ratios were higher at 15, 46, and 60 cm than at 30 cm and the base. Sound pulse rates were higher at 15 and 60 cm than at 30 and 46 cm. Overall, the mean rate for sites ≤60 cm from the base was 28 sounds/s. This rate was not significantly different from the mean of 43 sounds/s ($t = 1.0$, df = 7, $P > 0.17$) measured at 30 cm in four quadrants of O1 (Table 1). Several different physical and behavioral factors may have contributed to the variation observed in Fig. 2. For example, when the behavioral activity is uniform, the pulse rate is proportional to the number of insects (see below and Mankin et al. 2001) and the signal-to-noise ratio decreases with increasing distance from the source. Thus, the observed differences in amplitude and sound rate may be an indication that large numbers of termites were feeding on roots near the recording sites at 15 and 60 cm, and small numbers near 46 cm. The other recording sites may have been farther from termite feeding sites. However, the *C. formosanus* activity samples in Figs. 2 and 3 and a representative, 10-s segment of *R. flavipes* activity in Fig. 4 both show considerable variation in amplitude levels at single recording sites. Perhaps this variation was caused by different behaviors producing sounds of different signal intensity or by activity of widely distributed termites.

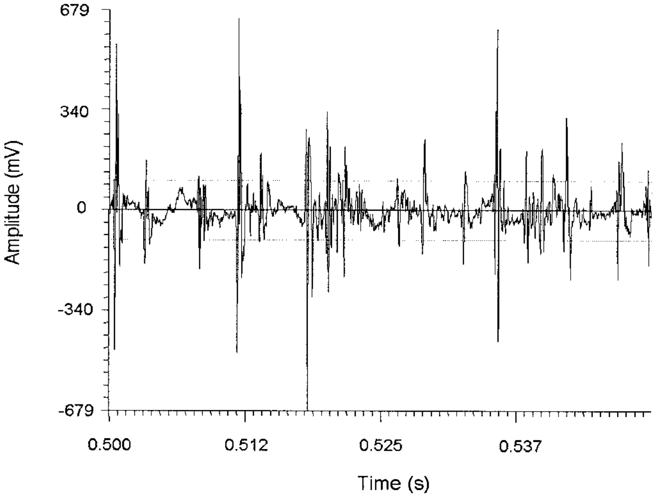

Fig. 3. Magnified (0.05-s) sample of signal recorded with accelerometer in soil beneath oak infested with *C. formosanus*: horizontal lines at ±100 mV indicate the threshold used by signal analysis program to identify potential termite sounds in background noise.

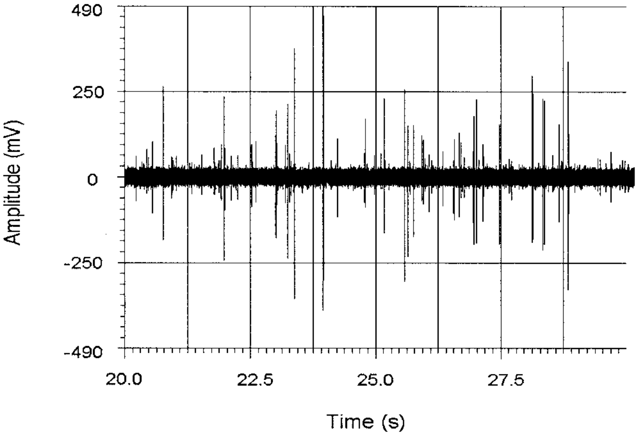

Fig. 4. Sample (10 s) of *R. flavipes* sounds recorded with accelerometer in soil beneath infested pine tree.

The rate of termite activity varied on the trunks as well as in the soil around infested trees. Table 1 lists activity rates in several recordings on the trunk and roots of P3. There was no obvious relationship between the level of activity at different sites in the soil and the levels detected at different sites on the trunk. The lack of correlation may occur because transverse transmission, cross-grain through the trunk attenuates more rapidly than longitudinal transmission through the grain up the trunk (Scheffrahn et al. 1993).

The sounds of all three species in this study had notable high-frequency components that easily distinguished them from most background sounds independently of whether they were recorded in soil or wood (Figs. 1 and 5). The *C. formosanus* profiles (Figs. 1a and 5 a-d) had relatively large contributions above two kHz compared with the *Reticulitermes* profiles (Fig. 1 b and c). The profiles of recordings from the trunk or roots of a tree (Fig. 5 a-c) had larger high-frequency contributions than those of recordings from the soil next to the tree (Fig. 5d). The latter profiles were similar to profiles of subterranean beetle grubs reported in Mankin et al. (2000). In this initial study, we did not attempt computer analysis to distinguish among termite species.

Computer Rating of Infestation Likelihood. Previous experience with field recordings of subterranean insects indicates that the likelihood of insect infestation at a recording site is proportional to the rate of sound pulses matching an appropriate sound profile. In Mankin et al. (2001), recording sites were rated by computer as having a high, medium, or low likelihood

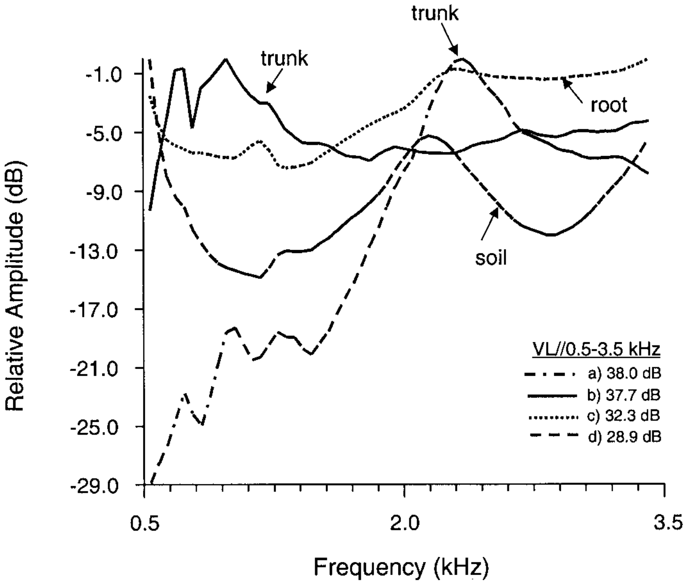

Fig. 5. Spectral profiles of *C. formosanus* recordings from accelerometer at sites on the trunk (a and b), in a root (c), and in the soil (d) at tree P3. Vibration levels between 0.5 and 3.5 kHz are set on a relative scale.

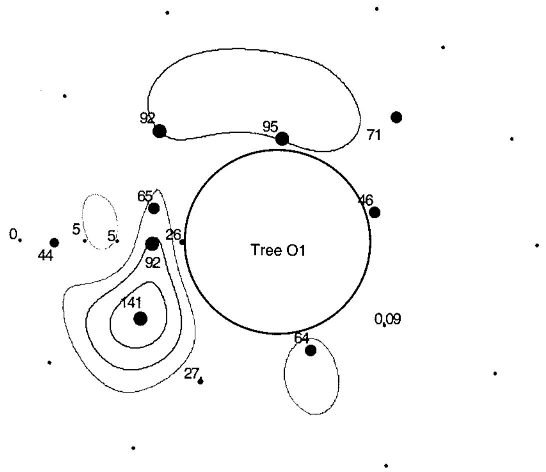

Fig. 6. Spatial distribution of termite sound activity around base of tree O1: numbers at recording sites indicate sound activity level in termite pulses/s; contours delineate areas of high and low activity. Dots at perimeter indicate 120 cm distance from center of tree.

of infestation if the insect sound pulse rates were >0.33, ≤0.33 and >0.033, and ≤0.003 pulses/s, respectively. Brandhorst-Hubbard et al. (2001) used a two-category rating system, with sound pulse rates >0.17, 0.45, and 0.6 pulses/s rated as having a high likelihood of infestation in three different tests. The lowest rate of sounds detected in any infested tree in this study was at P2 with 4.7 termite pulses/s (Table 1). The computer-rated likelihood of tree infestation consequently is identical to the Osbrink et al. (1999) survey and the listener ratings if the 0.33 pulses/s threshold in Mankin et al. (2001) is used as a prediction criterion for a high likelihood of infestation.

Termite Detection Range and Spatial Distribution of Sound Activity. Individual recordings were analyzed from nine positions around the base of O1 (Fig. 6) and six positions extending on a radius from the base of O1 (Fig. 2) to gauge the variation of activity around an infested tree. Although we did not record around building perimeters in this study, the same recording procedures could be used to search for subterranean tunnels of termites entering buildings. The measurements confirm that activity levels in soil vary widely over distances of a few centimeters, perhaps indicating the presence of tunnels that are not distributed randomly or systematically. These results are in agreement with previous studies where *C. formosanus* tunnel construction was skewed toward high-quality foraging sites (Hedlund and Henderson 1999, Campora and Grace 2001).

The measurements at O1 and other informal tests indicate that termites cannot be detected in soil over distances >15–20 cm from the inserted nail. Soil is an excellent sound insulator. In contrast, wood is an excellent sound transmitter, and *R. virginicus* workers could be detected easily at all recording sites up to 180 cm in the tests with termites in wood planks in an anechoic chamber. At the Southern Regional Research Center campus, however, background noise, especially vehicle and wind noise, often made it difficult to identify termites using an accelerometer attached to a screw in a tree trunk. In a high noise background, an acoustic emission detector would be a more practical instrument for termite detection from monitoring sites on the trunk.

Prediction of Infestation Level from Sound Activity. A goal of the study was to determine whether the termite populations at different recording sites could be estimated from an easily measured characteristic of the recording, e.g., the activity rate. To consider its potential as an indicator of the number of nearby termites, we examined the relationship between activity rate and the number of *R. flavipes* workers in wood trap blocks kept the laboratory over a 30-d period. The line of best fit (Fig. 7) was the equation,

$$\text{Log (sound rate)} = \text{A} + \text{B Log (no. termites} + 1),$$

where A = 0.019 ± 0.022 standard error (SE) is the intercept, and B = 0.16 ± 0.01 SE is the slope (SAS Institute 1988). The coefficients, A and B, have no units, and the activity rate is in units of termite pulses/s. The root mean square error was 0.027 and the coefficient of determination, r^2, was 0.55. Based on the regression line and the mean rate of sounds in the control, the minimum number of termites that could be detected in the trap reliably was ≈55 (Fig. 7, arrow). This is a density of ≈0.06 termites/cm^3 or 0.37 termites/g of wood. The number would be expected to depend on the species, the temperature, and the age and physiological status of the termites. In general, however, groups of 50 or fewer termites per 1-liter (150 g) trap block may not be easily detectable above the background noise. An increase by a factor of 10 in the termite number increased the sound rate by ≈1.5. Others who have found proportional relationships between sound pulse activity and termite numbers include Fujii et al. (1990), and Lewis and Lemaster (1991) and Scheffrahn et al. (1993), using acoustic emission detection systems. The latter found that 20 insects could be detected in a 7 by 4 by 4-cm block or 0.18 termites/cc, approximately the same as in this study. For low-frequency acoustic monitoring, a primary restriction on minimum detectable number is the signal-to-noise ratio, and for acoustic emission monitoring, the restriction is primarily the attenuation of signal intensity over distance.

Potential Applications. The results of this study confirm that acoustic monitoring techniques can be used for rapid detection of termites in outdoor urban environments. Under good conditions, active infestations can be detected in minutes rather than months, and the conditions under which detection would be difficult can be easily identified. For example, low-frequency acoustic methods would not be useful in cold weather when termite activity is minimal or in extremely noisy environments when termite activity is masked. Acoustic emission systems automatically filter out background noise even in wood (Robbins et al. 1991), but the range of detection is limited in soil because ultrasonic frequencies attenuate more rapidly

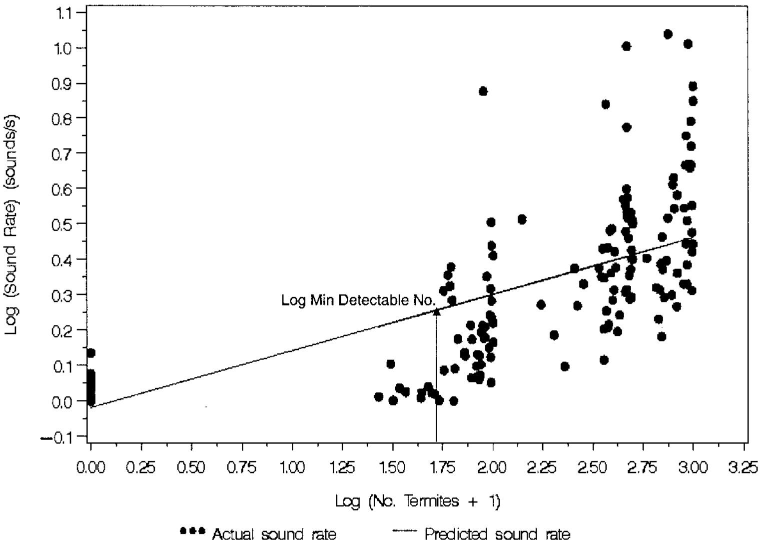

Fig. 7. Regression of *R. flavipes* sound activity rate on number of workers at recording site.

with distance than low frequencies. Such tradeoffs between detection range and discrimination reliability have led to avoidance of acoustic technology, even though commercial systems have been available for several years and are one of the best available methods for posttreatment inspection (e.g., use of acoustic emission systems by Scheffrahn et al. 1997, Weissling and Thoms 2000, Thoms 2000). However, recent improvements in technology and computer signal processing methods now enable applications and signal identification procedures that were previously considered unlikely.

Acknowledgments

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