Acoustic Detection of *Oryctes rhinoceros* (Coleoptera: Scarabaeidae: Dynastinae) and *Nasutitermes luzonicus* (Isoptera: Termitidae) in Palm Trees in Urban Guam

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ABSTRACT Adult and larval *Oryctes rhinoceros* (L.) (Coleoptera: Scarabaeidae: Dynastinae) were acoustically detected in live and dead palm trees and logs in recently invaded areas of Guam, along with *Nasutitermes luzonicus* Oshima (Isoptera: Termitidae), and other small, sound-producing invertebrates and invertebrates. The low-frequency, long-duration sound-impulse trains produced by large, active *O. rhinoceros* and the higher frequency, shorter impulse trains produced by feeding *N. luzonicus* had distinctive spectral and temporal patterns that facilitated their identification and discrimination from background noise, as well as from roaches, earwigs, and other small sound-producing organisms present in the trees and logs The distinctiveness of the *O. rhinoceros* sounds enables current usage of acoustic detection as a tactic in Guam's ongoing *O. rhinoceros* eradication program.

KEY WORDS invasive species, acoustic detection, eradication

Adult *Oryctes rhinoceros* (L.) Coleoptera: Scarabaeidae: Dynastinae) bore into and feed inside emerging fronds at the crowns of coconut (*Cocos nucifera* L.) and other palm trees in Southeast Asia and tropical Pacific islands, causing extensive damage (Gressitt 1953, Hinckley 1973, Bedford 1980, Jackson and Klein 2006). Frequent attacks by several adults may kill a tree. Larvae feed inside rotting logs of palms killed by adults or by high winds from typhoons that pass through the tropical Pacific annually. Introductions of *O. rhinoceros* into the Palau Islands and other originally uninfested regions have resulted in considerable economic harm to coconut palm plantations (Gressitt 1953).

O. rhinoceros was unknown in Guam until 2007 (Smith and Moore 2008), and due to the considerable potential for economic damage, the Tumon Bay hotel district was quarantined a few days after an adult female was discovered in the area. Mass trapping was initiated with commercially available aggregation pheromone oryctalure (ethyl 4-methyloctanoate) (Hallett et al. 1995, Ramle et al. 2005), and a program was established to remove or treat rotting coconut logs and other potential breeding and larval feeding sites.

Spot treatment of palms and breeding sites has been conducted with conventional and injectable insecticides (Smith and Moore 2008).

Visual inspection of frond and trunk damage is the most commonly used method of detecting *O. rhinoceros* adults; however, infestations cannot be detected easily from the ground until well after significant damage has occurred. Because adults, larvae, and pupae are known to produce audible sounds (Gressitt 1953, Mini and Prabhu 1990), it was of interest to determine whether adults feeding and moving in the crowns of live trees and larvae feeding in standing, dead trunks can be detected by acoustic methods (e.g., Mankin et al. 2000, 2002, 2008a,b). Previous experience with detection of insect sounds in trees (e.g., Mankin et al. 2008b) suggested that a combination of spectral and temporal pattern features of detected sounds could be used to distinguish *O. rhinoceros* signals from nontarget signals in the noisy urban areas of the quarantine zone. A large insect like *O. rhinoceros* might perform boring and feeding activities that produced louder and longer sounds than those produced by other small insects that also were associated with palm trees, including *Pycnoscelus surinamensis* (L.) (Blattodea: Blaberidae), *Brontispa palauensis* (Esaki & Chujo) (Coleoptera: Chrysomelidae) (Muniappan 2002), *Chelisoches morio* (F.) (Dermaptera: Chelisochidae), and tenebrionids. Here, we report on a study conducted to determine the feasibility of incorporating acoustic detection methods into the ongoing program to isolate and eradicate breeding populations.

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Materials and Methods

Records were collected over an 11-d period from 11 live palm trees, six dead palm trees, seven logs, and five stumps that were easily accessible and available for (destructive) inspection at several different locations in the Tumon Bay hotel district quarantine zone. External verification of the insects present at each site was performed within ≈24 h after recording by felling a tree if it was standing, splitting open the trunk, log, or stump tissue with axes and knives, and sorting through the separated pieces. The surveyed locations included the grounds of a hospital, a hotel, a retirement complex, a shopping center, and three houses, as well as a rubbish pile. Although *O. rhinoceros* were known to be present in the quarantine zone, none of the individual trees, logs, or stumps in the field study had been inspected previously. Temperatures were ≈28–31°C at the times of recording.

To gain additional knowledge of the characteristics of signals produced by larval and adult *O. rhinoceros*, records were collected also from separate groups of *O. rhinoceros* larvae and adults maintained in a rearing facility at the University of Guam. These beetles were held in 30- by 24- by 24-cm plastic rearing cages containing pieces of sugar cane and palm trunk. The laboratory studies are described separately from the field studies in the last section of the Results because the spectral characteristics of the sounds depend strongly on the substrate in which insects are moving and feeding (Mankin et al. 2008).

Acoustic Sensors and Recording Procedures. Signals were collected from accelerometers attached to charge amplifiers (Mankin et al. 2000, 2001, 2002). The amplified signals were saved on a dual-channel, digital audio recorder sampling at 44.1 kHz (24 bits). In recordings at a survey location, the accelerometers were attached magnetically to 30-cm-long spikes, inserted into the wood a few minutes before recording. In laboratory recordings of *O. rhinoceros* held in rearing containers, the accelerometer was attached to the rearing container or to a small nail inserted into one of the palm pieces on which the insects were feeding.

Listeners (see *Acknowledgments*) could monitor the signals using headphones attached to the recorder, thereby avoiding levels of wind or street noise high enough to mask insect sounds. Wind noise caused delays in 20–30% of the recording trials, but in all cases there were sufficient intervals of reduced background noise to permit useful recordings of insect sounds for periods of 45 s or longer. In the absence of background interference, records were collected for 180 s or longer. Dual-channel recordings from two accelerometers were obtained from several field sites, in which cases the channel with the greatest clarity was selected for analysis.

Digital Signal Processing and Classification. After the recording sessions each day were completed, the recorded signals were transferred to a laptop computer and initial analyses of their spectral and temporal characteristics were conducted using Raven 1.3 software (Charif et al. 2008). Because much of the

signal below 200 Hz was background noise and no important signal features were observed >5 kHz, the signals were band-pass filtered between 0.2 and 5 kHz to facilitate subsequent analyses. In the initial screenings, we confirmed the presence of groups (trains) of discrete, 3–10-ms impulses separated by intervals <250 ms. Such trains had appeared frequently in recordings at sites where insects were recovered in previous studies (Zhang et al. 2003a,b; Mankin et al. 2008a,b). Trains containing 15 or more impulses were a focus of analysis because they often were identified as insect sounds in playbacks of recordings from infested sites, but trains containing only small numbers of impulses, as well as signals without any 3–10-ms impulses, usually were interpreted as background noise (Mankin et al. 2008b).

The impulses and impulse trains detected in the recordings were analyzed with customized software, DAVIS (Digitize, Analyze, and Visualize Insect Sounds, Mankin 1994, Mankin et al. 2000), which discarded long-duration, low frequency background noise (Mankin et al. 2007, 2008a,b) and then compared the spectrum of a 512-point time-slice centered around the peak of each impulse against averaged spectra (spectral profiles) of independently verified insect-produced signals and impulsive, tree bending-grinding noises (see next section). The spectral comparisons were performed after normalizing the acceleration (Mankin and Benshemesh 2006).

Insect and Background-Noise Spectral Profiles. Spectral profiles (Mankin 1994, Mankin et al. 2000) were constructed from background noise impulse trains and four types of insect sound impulse trains, two of which were produced by the primary targets, adult and larval *O. rhinoceros*. An adult *O. rhinoceros* profile, *rhino_a*, was averaged from 33 consecutive impulse trains collected at a live palm where an adult was recovered, and a larval profile, *rhino_l*, from 35 consecutive impulse trains collected at the log where 72 larvae were recovered. One of two nontarget-insect profiles, *termite*, was constructed from 233 consecutive impulse trains produced in a dead palm where only *Nasutitermes luzonicus* Oshima (Snyder and Francia 1960, Su and Scheffrahn 1998) were recovered, and the second from 45 consecutive impulse trains produced in a live palm where two nontarget species, *P. surinamensis* and *B. palauensis*, were the only organisms recovered. A background noise profile was generated as a spectral average of wind-induced tapping and trunk bending and grinding that produce short, broadband sound impulses (e.g., Fukuda et al. 2007). A series of 38 consecutive impulse trains recorded at an uninfested palm were used in constructing this profile.

After the profiles mentioned above were constructed from individual files, the complete set of files was reviewed in DAVIS, which discarded impulses from further analysis if their spectra failed to match the *rhino_a*, *rhino_l*, or *termite* spectral profiles within an empirically determined difference threshold, T_s, or if they matched one of the two nontarget profiles more closely than any insect sound profile. The occurrence

times of impulses that matched an insect sound profile (valid impulses) were saved in an impulse-sequence spreadsheet and labeled according to which of the three spectral profiles they matched best.

Temporal Pattern Analyses. The impulse sequences were screened to identify and characterize groups (trains) of impulses that listeners typically classify as separate, individual sounds, i.e., groups of impulses separated by intervals <250 ms (Mankin et al. 2008b). Each train was labeled according to the spectral profile matched by a plurality of its impulses. The beginning and ending times of impulse trains, their labels, and the number of impulses per train, n_t, were stored in separate train-sequence spreadsheets for each recording.

Train-sequence spreadsheets were screened further to determine the range of impulse counts found in trains of each profile. Initially, we examined the distributions of n_t in recordings where only *O. rhinoceros* was present at a site, and trains with >10 impulses were played back through the audio feature in Raven to determine whether a listener assessed them as insect sounds, background noise, or unclassifiable. Based on these screenings, minimum counts, $n_{min\text{-}rhino\_a}$ and $n_{min\text{-}rhino\_l}$, were estimated for trains with sufficient impulse counts to be classified as insect sounds, designated hereafter as bursts (Mankin et al. 2008a,b). Because termites were found at many recording sites, we conducted a similar analysis for sites where only termites were present, and a minimum count, $n_{min\text{-}termite}$, was estimated to classify *termite* trains of sufficient size as *termite* bursts.

We then reprocessed the complete set of train-sequence spreadsheets. Trains labeled as *rhino_a* or *rhino_l*, with $n_t > n_{min\text{-}rhino\_a}$ or $n_t > n_{min\text{-}rhino\_l}$, were set as *rhino_a* or *rhino_l* bursts, respectively. Trains labeled as *termite*, with $n_t > n_{min\text{-}termite}$, were set as *termite* bursts. These procedures were similar to those used previously to specify bursts produced by hidden larvae of two other insect pest species, *Anoplophora glabripennis* (Motschulsky) (Mankin et al. 2008b) and *Rhynchophorus ferrugineus* (Olivier) (Mankin et al. 2008a).

Computer-Rated Likelihood of Infestation. Based on previous occurrences of strong associations between insect infestations and trains or bursts of insect sound impulses (Mankin et al. 2008a,b), we considered the possibility that such associations occurred also for *O. rhinoceros* infestations and *rhino_l* or *rhino_a* trains or bursts, as well as for *N. luzonicus* infestations and *termite* trains or bursts. We therefore constructed indicators of infestation likelihood (Table 1) by using procedures similar to those described in Mankin et al. (2007). First, cutoffs were estimated for rates of trains and bursts, l_{ower}, below which infestations rarely occurred, and for rates, u_{pper}, above which infestations were likely (see column C, Table 1). The cutoffs were estimated from the observed distributions of *O. rhinoceros* and *termite* train and burst rates at infested and uninfested sites. The indicator values for *O. rhinoceros* and *termite* trains and bursts were set as h_{igh}, m_{edium}, or l_{ow}, as denoted in Table 1. Further-

Table 1. Names of indicator (A) and rate (B) variables for *O. rhinoceros* and *N. luzonicus* trains and bursts, and values of cutoff rates (C), below which infestations rarely occurred (l_{ower}) and above which infestations were likely (u_{pper}), estimated from the observed distributions of *O. rhinoceros* and *termite* trains and bursts at infested and uninfested sites (see Results)

(A) Indicator variable	(B) Rate variable (unit)	(C) Cutoff rates (no./min)	
		l_{ower}	u_{pper}
$i_{rhino\_l\text{-}t}$	$r_{rhino\_l\text{-}t}$ (trains/min)	25.0	50.0
$i_{rhino\_l\text{-}b}$	$r_{rhino\_l\text{-}b}$ (bursts/min)	0.5	5.0
$i_{rhino\_a\text{-}t}$	$r_{rhino\_a\text{-}t}$ (trains/min)	15.0	35.0
$i_{rhino\_a\text{-}b}$	$r_{rhino\_a\text{-}b}$ (bursts/min)	0.5	2.0
$i_{termite\text{-}t}$	$r_{termite\text{-}t}$ (trains/min)	15.0	35.0
$i_{termite\text{-}b}$	$r_{termite\text{-}b}$ (bursts/min)	5.0	10.0

In each row, the indicator variable value is h_{igh}, for rate $\geq$ upper cutoff; m_{edium}, for upper cutoff > rate $\geq$ lower cutoff; and l_{ow}, otherwise, where the labels "rhino" refer to *O. rhinoceros* rates and cutoffs, "termite" to *termite* rates and cutoffs, "_l" to larvae, "_a" to adults, "t" to trains, and "b" to bursts.

more, we considered two comprehensive indicators of *O. rhinoceros* infestation, combining the cases of larval and adult infestation, i.e.,

$$i_{rhino\text{-}t} =$$

$$\begin{cases} h_{igh} & \text{if } i_{rhino\_l\text{-}t} = h_{igh} \text{ or } i_{rhino\_a\text{-}t} = h_{igh} \\ m_{edium} & \text{if } i_{rhino\_l\text{-}t} = m_{edium} \text{ and } i_{rhino\_a\text{-}t} < h_{igh} \\ & \text{or } i_{rhino\_a\text{-}t} = m_{edium} \text{ and } i_{rhino\_l\text{-}t} < h_{igh} \\ l_{ow} & \text{otherwise, with indicator values specified as in} \end{cases}$$

[1]

Table 1, and similarly,

$$i_{rhino\text{-}b} =$$

$$\begin{cases} h_{igh} & \text{if } i_{rhino\_l\text{-}b} = h_{igh} \text{ or } i_{rhino\_a\text{-}b} = h_{igh} \\ m_{edium} & \text{if } i_{rhino\_l\text{-}b} = m_{edium} \text{ and } i_{rhino\_a\text{-}b} < h_{igh} \\ & \text{or } i_{rhino\_a\text{-}b} = m_{edium} \text{ and } i_{rhino\_l\text{-}b} < h_{igh} \\ l_{ow} & \text{otherwise.} \end{cases}$$

[2]

Finally, the distributions of h_{igh}, m_{edium}, and l_{ow} likelihood of infestation of *O. rhinoceros* or termites at recording sites were compared at infested and uninfested sites using the Wilcoxon two-sample exact test (Proc NPAR1WAY, SAS Institute 2004) under the null hypothesis that the distributions of the likelihood of infestation were independent of whether the sites were infested or uninfested.

Results

Three of 29 recording sites in the quarantine zone were found to contain *O. rhinoceros.* Eight other sites were free of sound-producing organisms. No *O. rhinoceros* were found at the remaining sites, but other sound-producing organisms were present, including *B. palauensis, C. morio, P. surinamensis,* tenebrionids, diplopodans, tree frogs, and geckos, hereafter denoted as nontarget organisms. *Nasutitermes luzonicus,* found
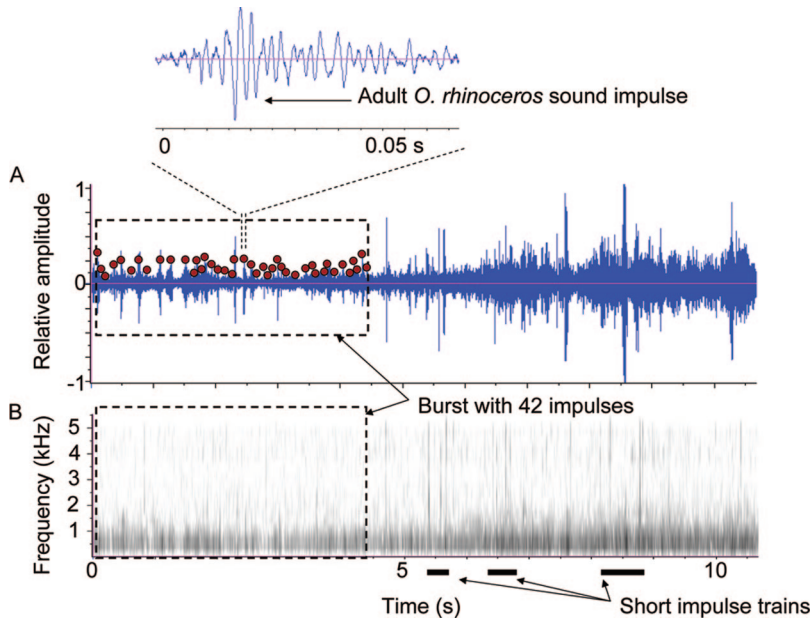
Fig. 1. Oscillogram (A) and spectrogram (B) of signals recorded by accelerometer from an *O. rhinoceros* adult in a palm tree, with an individual sound impulse expanded in the inset. Signals enclosed by dotted lines indicate a long series (train) of impulses that was classified by computer analysis as an *O. rhinoceros* burst. The 42 impulses included in the burst are noted with dots. Three subsequent short impulse trains are underlined below the time scale. Darker shades in the spectrogram indicate frequencies with higher signal energy at the specified time. (Online figure in color.)

in five dead trees and logs that did not contain *O. rhinoceros*, were among the most abundant nontarget sound-producing organisms.

A 10-s sample of signals recorded at a site with an adult *O. rhinoceros* is shown in Fig. 1A and B. The sample contains multiple, 3–10-ms impulses, one of which is expanded in the inset of Fig. 1A. Four impulse trains occur in the sample. The first train, classified by the DAVIS signal analysis program as a *rhino_a* burst, includes 42 impulses that are marked by dots in the dashed rectangle. Three subsequent, shorter trains are underlined below the time scale. The impulses were broad-band signals with dominant peaks below ≈2 kHz and secondary peaks between 4 and 5 kHz (Fig. 1B). Background noise is visible in Fig. 1B as a dark band extending through the sample interval, primarily between 0 and 1.5 kHz, sometimes expanding to 2.5 kHz during periods of high wind.

Signals produced by *O. rhinoceros* larvae usually were lower in amplitude, but similar in duration to those produced by adults, as in the 10-s sample in Fig. 2A and B, recorded from a palm log where 72 larvae were recovered. The sample includes a short train (n_t = 13 impulses) underlined below the time scale, followed by a longer train that the DAVIS program classified as a *rhino_l* burst (n_t = 28 impulses marked by dots in the dashed box), an impulse of which is expanded in the inset of Fig. 2A. The larval and adult signals had similar spectral characteristics, shown in the spectral profiles of Fig. 3 along with a spectral profile for *N. luzonicus*, a profile for signals produced by two nontarget in-

sects, *P. surinamensis* and *B. palauensis*, and a profile for background noise signals produced by wind- and tree-grinding.

Temporal Pattern Analysis. To consider the possibility that *O. rhinoceros* might perform activities producing louder and longer sounds than from roaches and other small insects in the palm trees, we examined the distribution of numbers of valid impulses in trains recorded from sites where only *O. rhinoceros* was recovered (three sites), and also examined the distribution of impulses at sites containing only nontarget organisms (14 sites). The fraction of *O. rhinoceros* trains with high impulse counts was greater for recordings in trees where *O. rhinoceros* was recovered than for recordings in trees with only nontarget organisms. Considering trains where the majority of impulses matched the *rhino_l* profile, for example, 5.5% of 396 trains contained >20 impulses in *O. rhinoceros* recordings, compared with 2.5% of 1,440 trains in nontarget-organism recordings. In trains where the majority of impulses matched the *rhino_a* profile, 10.3% of 143 trains contained >20 impulses in *O. rhinoceros* recordings, compared with 0.5% of 1407 trains in nontarget-organism recordings. We therefore set larval- or adult-profile trains with $n_t > n_{min-rhino\_l} = n_{min-rhino\_a} = 20$ impulses as *rhino_l* or *rhino_a* bursts, respectively (see Materials and Methods).

Because *N. luzonicus* and other termites can be important pests in human structures (Acda 2007) and were encountered frequently during the study, we also examined the distributions of the numbers of impulses in *termite* trains. In this case, the distribu-
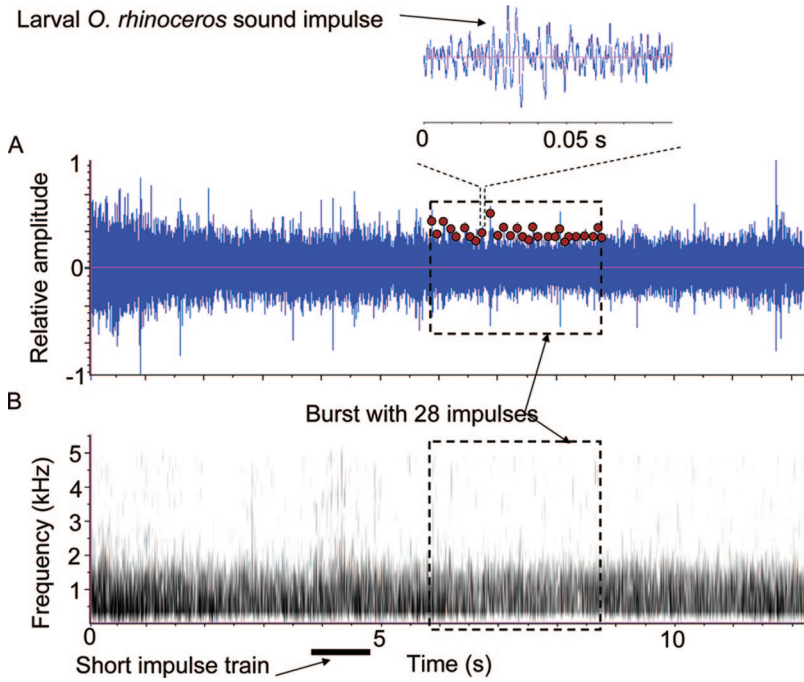
Larval *O. rhinoceros* sound impulse

Fig. 2. Oscillogram (A) and spectrogram (B) of signals recorded by accelerometer from *O. rhinoceros* larvae in a palm log, with an individual sound impulse expanded in the inset. Signals enclosed by dotted lines indicate a group (train) of impulses that was classified by computer analysis as an *O. rhinoceros* burst. The 28 impulses included in the burst are noted with dots. A shorter impulse train is underlined below the time scale. Darker shades in the spectrogram indicate frequencies with higher signal energy at the specified time. (Online figure in color.)

tions of *termite* trains were similar for infested and uninfested sites but the total numbers of *termite* trains with >15 impulses per train was much greater at sites where *N. luzonicus* were present. The minimum count for a *termite* burst was estimated at $n_{min-termite} = 15$ impulses, slightly fewer than the

minimum count for a *rhino* burst, and thus shorter in duration.

Distribution of *O. rhinoceros* Trains and Bursts Among Infested and Uninfested Sites. The complete set of field recordings was analyzed in DAVIS by using the profiles in Fig. 3 to consider the association
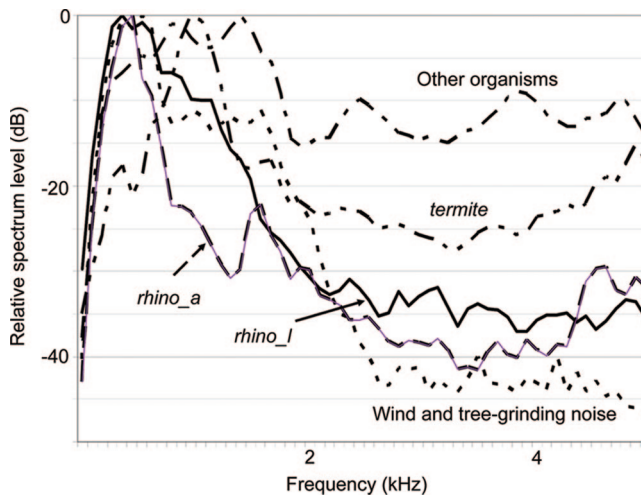
Fig. 3. Spectral profiles of series of impulses recorded from an *O. rhinoceros* adult in a live palm tree (*rhino_a*, dashed line), *O. rhinoceros* larvae in a log (*rhino_l*, solid line), *N. luzonicus* in a dead tree (*termite*, dash-dot-dotted line), other organisms in a live palm (dash-dotted line), and wind and bending-grinding noises in a live tree (dotted line). Spectrum level is relative to the maximum acceleration measured in the 0.2- to 5-kHz reference range. (Online figure in color.)

Table 2. Rates (number per minute) of *O. rhinoceros* larval-profile trains, r_{rhino_l-t}, and bursts, r_{rhino_l-b}, adult-profile trains, r_{rhino_a-t}, and bursts, r_{rhino_a-b}, and termite-profile trains, $r_{termite-t}$, and bursts, $r_{termite-b}$, detected in palm trees or logs holding specified numbers of *O. rhinoceros* larvae or adults, arranged in order of descending larval-profile burst rates, r_{rhino_l-b}, at infested and uninfested sites

Larval profile (r_{rhino_l})		Adult profile (r_{rhino_a})		Termite profile ($r_{termite}$)		No. (stage)
Trains	Bursts	Trains	Bursts	Trains	Bursts	
9.81	2.58	15.50	8.27	4.13	2.07	3 (larvae)
53.92	1.23	17.62	0.00	3.06	0.15	72 (larvae)
2.62	0.00	38.61	2.25	4.50	1.50	1 (adult)
6.32	1.26	44.27	0.00	3.79	1.26	
61.58	0.89	18.16	0.44	4.87	0.00	
6.03	0.00	0.00	0.00	39.17	3.01	
7.59	0.00	0.00	0.00	24.28	3.79	
0.00	0.00	0.00	0.00	9.28	9.28	
8.17	0.00	19.60	0.00	1.63	0.00	
24.55	0.00	0.00	0.00	13.75	1.96	
6.28	0.00	3.14	0.00	28.25	9.42	

Table 4. Rates (number per minute) of *O. rhinoceros* larval-profile trains, r_{rhino_l-t}, and bursts, r_{rhino_l-b}, *O. rhinoceros* adult-profile trains, r_{rhino_a-t}, and termite-profile trains, $r_{termite-t}$, and bursts, $r_{termite-b}$, detected in palm stumps from which nontarget sound-producing organisms but no *O. rhinoceros* or termites were recovered, ranked in order of descending rates of *termite* bursts, $r_{termite-b}$

Larval (r_{rhino_l})		Adult (r_{rhino_a})	Termite ($r_{termite}$)		No. insects[a]
Trains	Bursts	Trains	Trains	Bursts	
1.72	0.00	0.00	39.92	12.88	2
5.01	0.00	0.00	30.08	12.53	3
6.90	1.70	0.50	25.19	9.50	3[b]
0.75	0.00	0.00	9.01	7.13	4
35.77	0.00	6.71	0.00	0.00	1

Note that the rate of rhino_a bursts was $r_{rhino\_a-b} = 0.0$ bursts/min for all five stumps.

[a] *B. palauensis*, *C. morio*, and *P. surinamensis*.
[b] In addition, a tree frog and a gecko were recovered from this stump.

between the presence or absence of *O. rhinoceros* infestation and the rates of *rhino_l* and *rhino_a* trains and bursts. Although trains that matched either the *O. rhinoceros* larval or adult profile appeared at low rates in the recordings at uninfested sites (Table 2), bursts that matched these profiles were detected at only two of eight uninfested sites. Trains and bursts that matched one or both profiles were detected at rates >1 per min at all sites containing *O. rhinoceros.* Rates of *termite* trains and bursts were low at sites with *O. rhinoceros* and no termites were found at these sites. The rates of *termite* trains and bursts were high at sites where termites were found (Table 3).

Impulse trains that matched the adult or larval *O. rhinoceros* profiles were observed in recordings where only nontarget organisms were recovered but generally at lower rates than observed at sites where *O. rhinoceros* were recovered (Tables 3 and 4). No *rhino_a* bursts were detected in recordings from

stumps, but *rhino_l* bursts were detected in one stump (Table 4).

Given the positive association found between the rates of *O. rhinoceros* bursts and the presence of *O. rhinoceros* at a recording site, we considered the construction of indicators for automated rating of infestation likelihood, analogous to train- and burst-rate indicators used successfully to detect infestations of other insects in wood in previous studies (Mankin et al. 2008a,b). In constructing the indicators, lower and upper cutoff rates (column C in Table 1) were estimated from the distributions of trains rates, burst rates, and *O. rhinoceros* counts in Tables 2–4. Rates of larval- and adult-profile trains and bursts below their estimated l_{ower} cutoff rates in column C of Table 1 seemed to be associated with a l_{ow} likelihood of infestation. Rates greater than or equal to their estimated u_{pper} cutoff rates in Table 1 seemed to be associated with a h_{igh} likelihood of infestation. The resultant ratings of infestation likelihood are listed in Table 5. A statisti-

Table 3. Rates (number per minute) of *O. rhinoceros* larval-profile trains, r_{rhino_l-t}, and bursts, r_{rhino_l-b}, adult-profile trains, r_{rhino_a-t}, and bursts, r_{rhino_a-b}, and termite-profile trains, $r_{termite-t}$, and bursts, $r_{termite-b}$, detected in palm trees and logs where only nontarget sound-producing organisms were recovered, listed in order of descending rates of *termite* bursts, $r_{termite-b}$

Larval (r_{rhino_l})		Adult (r_{rhino_a})		Termite ($r_{termite}$)		No. invert.[a]	No. vert.[b]
Trains	Bursts	Trains	Bursts	Trains	Bursts		
0.22	0.00	0.00	0.00	29.44	10.62	—[c]	—
1.01	0.00	0.00	0.00	25.13	10.05	—[c]	—
11.54	0.38	0.00	0.00	41.54	9.23	—[c]	—
12.69	0.67	0.00	0.00	36.07	8.68	2	—
5.17	0.40	1.59	0.40	20.67	6.76	4	—
0.89	0.00	25.48	1.79	7.60	3.58	3	2
10.94	1.86	25.81	0.21	9.50	3.30	3	2
31.60	0.72	38.07	0.00	6.46	1.44	5	—
26.85	0.75	38.65	0.00	6.27	0.50	—[c]	—
5.86	0.90	44.63	1.80	1.35	0.45	3	2
37.85	0.49	5.85	0.00	18.93	0.29	—[c]	—
3.45	0.00	59.42	0.69	0.00	0.00	3	2
0.00	0.00	40.84	0.00	0.00	0.00	2	—

[a] *B. palauensis*, *C. morio*, *P. surinamensis*, tenebrionids, diplopodans, with uncounted (>10) *N. luzonicus* present where noted ([c]).
[b] Tree frogs, geckos.
[c] *N. luzonicus.*

Table 5. Distributions of computer-rated likelihood of *O. rhinoceros* infestation at sites where larvae or adults were confirmed absent or present, by using indicators estimated from observed distributions of rates of *rhino_l* or *rhino_a* impulse trains or bursts

Infestation likelihood rating	No. sites with *O. rhinoceros* absent or present, rated by trains or bursts indicator			
	Trains[a]		Bursts[b]	
	Absent	Present	Absent	Present
l_{ow}	13	0	17	0
m_{edium}	6	1	9	1
h_{igh}	7	2	0	2

[a] $P = 0.17$ that trains comprehensive indicator, $i_{rhino-t}$, is independent of absence or presence of *O. rhinoceros* at recording site (Wilcoxon two-sample exact test: $S = 67$, $Z = 1.6535$, $N = 29$), where indicator value is l_{ow} if ($r_{rhino\_l-t} < 25.0$ and $r_{rhino\_a-t} < 15.0$), h_{igh} if ($r_{rhino\_l-t} > 50.0$ or $r_{rhino\_a-t} > 35.0$), and otherwise m_{edium}.
[b] $P = 0.003$ that bursts comprehensive indicator, $i_{rhino-b}$, is independent of presence or absence of *O. rhinoceros* at recording site (Wilcoxon two-sample exact test: $S = 79.5$, $Z = 2.7963$, $N = 29$), where indicator value is l_{ow} if ($r_{rhino\_l-b} < 0.5$ and $r_{rhino\_a-b} < 0.5$), h_{igh} if ($r_{rhino\_l-b} > 5.0$ or $r_{rhino\_a-b} > 2.0$), and otherwise m_{edium}.

Table 6. Distributions of computer-rated likelihood of termite infestation at sites where *N. luzonicus* were confirmed absent or present, by using indicators estimated from observed distributions of rates of termite impulse trains or bursts

Infestation likelihood rating	No. sites with *N. luzonicus* absent or present, rated by trains or bursts indicator			
	Trains[a]		Bursts[b]	
	Absent	Present	Absent	Present
l_{ow}	14	1	15	2
m_{edium}	3	1	4	1
h_{igh}	2	3	0	2

[a] $P = 0.02$ that the trains indicator, $i_{termite-t}$, is independent of presence or absence of termites at recording site (Wilcoxon two-sample exact test: $S = 91.5$, $Z = 2.3495$, $N = 24$), where indicator value is l_{ow} if $r_{termite-t} < 15.0$, h_{igh}, if $r_{termite-t} > 35.0$, and otherwise m_{edium}.
[b] $P = 0.03$ that bursts indicator, $i_{termite-b}$, is independent of presence or absence of termites at recording site (Wilcoxon two-sample exact test: $S = 85.0$, $Z = 1.9608$, $N = 24$), where indicator value is l_{ow} if $r_{termite-b} < 5.0$, h_{igh} if $r_{termite-b} > 10.0$, and otherwise m_{edium}.

cally significant relationship was found between the bursts comprehensive indicator, $i_{rhino-b}$ (equation 2), and the presence or absence of *O. rhinoceros*, but the relationship for the trains comprehensive indicator, $i_{rhino-t}$ (equation 1, was not statistically significant.

Distributions of *termite* Trains and Bursts Relative to *N. luzonicus* and *O. rhinoceros* Infestations. Termites were encountered at five recording sites, and we considered whether the rates of *termite* trains, $r_{termite-t}$, and bursts, $r_{termite-b}$, could be used to construct indicators of termite infestation likelihood similar to the indicators of *O. rhinoceros* infestation. The distributions of burst rates, trains rates, and *N. luzonicus* counts in Tables 2 and 3 were used to estimate l_{ower} cutoff rates, below which *N. luzonicus* were rarely present, and u_{pper} cutoff rates, above which *N. luzonicus* were likely to be found (Table 1). It should be noted that the termite analysis did not include results from the five stumps in Table 4 because it was not possible to determine conclusively that termites were present or absent in the unexcavated portions of the root system.

Computer ratings of infestation likelihood based on the above cutoff rate estimates are listed in Table 6. Both trains and bursts indicators were found to be significantly associated with the presence of *N. luzonicus* at the recording sites. It was thus possible in this study to predict independently the presence or absence of both *O. rhinoceros* and termites at a recording site using acoustic indicators.

Signals From *O. rhinoceros* Confined in Cages or Rearing Boxes. To obtain confirmatory recordings of adult-produced sounds, 14 adults collected from pheromone-baited traps were placed in separate cages that were attached to palm trees with an open side permitting entry to the trunk. Recordings were collected on the following day, and the cages were subsequently removed. Adult-profile trains were detected in the recordings from all of the artificially infested palm trees. However, adult-profile bursts were detected at only one tree. Upon inspection, two of the adults had

died without cutting into the tree, two were alive but had caused no damage, and 10 others had burrowed 5 cm or more into the trunk.

Groups of larvae and adults in rearing boxes produced audible sounds at rates of 6 to 7 trains per min in pieces of palm tree trunk and sugarcane. Although the spectral patterns were different from those of sounds produced in trees and logs, due to the different substrates, both larvae and adults conducted activities with impulse rate patterns similar to those in the natural infestations. In the boxes with feeding larvae, the larvae typically oriented head-to-tail inside an approximately spherical chamber, which they had burrowed out of the palm trunk. They moved in a circular or toroidal pattern, with a moving constriction and then an expansion that began at the tip of the abdomen and moved toward the head. The movement produced an audible sound, and the timing of a typical burst corresponded to the timing of the constriction–expansion pattern.

Discussion

The notable audibility of sounds produced by *O. rhinoceros* adults and larvae has attracted the interest of several generations of entomologists (Darwin 1871, Gressitt 1953, Mini and Prabhu 1990). Thus, it is no surprise that adult *O. rhinoceros* scraping and chewing movements and larval burrowing activities produce sounds with distinctive spectral and temporal patterns that facilitate detection by acoustic instruments in urban environments. Other examples have been reported of leafminer larvae (Bacher et al. 1996, Meyhöfer and Casas 1999, Castellanos and Barbosa 2006, Casas and Magal 2007, Low 2008) and termites (Inta et al. 2009) that perform evasive or avoidance behaviors upon detecting distinctive spectral and temporal patterns in sounds produced by parasitoids and predators. Distinctive frequency and temporal patterns of predator vibrations are known to elicit escape hatching of red-eyed tree frogs (Caldwell et al. 2009). The sounds of burrowing moles have been

shown to elicit escape activities in earthworms and have been mimicked by "worm grunters" who harvest earthworms for fishing (Catania 2008, Mitra et al. 2009). To survive, animals of many different species routinely detect and identify distinctive spectral and temporal patterns of acoustic signals produced by other organisms, and such capability was perfected many thousands of years before the development of equivalent digital signal processing methods that are only now are coming into use.

It is likely, however, that the reliability of *O. rhinoceros* detection could be enhanced in the future beyond what was accomplished in this study. Larvae and adults (Mankin et al. 2009) both produce stridulations, for example, and more detailed characterization of stridulations and scraping motions could lead to further increases in reliability of detection. In addition, the short trains underlined in Figs. 1 and 2 possibly were produced by *O. rhinoceros*, but did not meet the criterion of $n_{min-rhino\_a}$ and $n_{min-rhino\_l} = 20$ impulses per train, equivalent to a relatively long, 60–200-ms minimum duration, adopted to reduce false-positive identifications of background noise or nontarget insects as *O. rhinoceros* sounds. Identification of multiple insect-sound patterns that are unlikely to occur randomly in background sounds can lead not only to improved detection methods but also to improved understanding of insect behavior.

The success of the detection tests conducted in this study suggests that acoustic methods could be incorporated beneficially into the ongoing program to eradicate the introduced *O. rhinoceros* infestations from Guam. The *O. rhinoceros* signals are distinctive, which facilitates their identification by scouts or by subsequent computer analyses of recorded signals. This helps enable detection of active adults in crowns of live trees and larvae in standing dead trunks that otherwise might escape detection. In each survey location, the scout can decide separately at each tree whether a visual inspection is sufficient to determine the presence or absence of infestation, or if time is available to attach an acoustic sensor to the trunk and listen for distinctive sounds produced by *O. rhinoceros*. The additional time needed for recording is 5–15 min per tree, which often is less than the time needed to move between two separate survey locations.

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