

## Acoustic Detection of *Rhynchophorus ferrugineus* (Coleoptera: Dryophthoridae) and *Oryctes elegans* (Coleoptera: Scarabaeidae) in *Phoenix dactylifera* (Arecales: Arecaceae) Trees and Offshoots in Saudi Arabian Orchards

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### Abstract

*Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Dryophthoridae) larvae are cryptic, internal tissue-feeding pests of palm trees that are difficult to detect; consequently, infestations may remain hidden until they are widespread in an orchard. Infested trees and propagable offshoots that develop from axillary buds on the trunk frequently are transported inadvertently to previously uninfested areas. Acoustic methods can be used for scouting and early detection of *R. ferrugineus*, but until now have not been tested on multiple trees and offshoots in commercial date palm orchard environments. For this report, the acoustic detectability of *R. ferrugineus* was assessed in Saudi Arabian date palm orchards in the presence of commonly occurring wind, bird noise, machinery noise, and nontarget insects. Signal analyses were developed to detect *R. ferrugineus* and another insect pest, *Oryctes elegans* Prell (Coleoptera: Scarabaeidae), frequently co-occurring in the orchards, and discriminate both from background noise. In addition, it was possible to distinguish *R. ferrugineus* from *O. elegans* in offshoots by differences in the temporal patterns of their sound impulses. As has been observed often with other insect pests, populations of the two species appeared clumped rather than uniform or random. The results are discussed in relation to development of automated methods that could assist orchard managers in quickly identifying infested trees and offshoots so that *R. ferrugineus* infestations can be targeted and the likelihood of transferring infested offshoots to uninfested areas can be reduced.

**Key words:** red palm weevil, date palm fruit stalk borer, scouting, pest management

*Rhynchophorus ferrugineus* (Olivier) is an important pest of coconut palms, *Cocos nucifera* L. (Arecales: Arecaceae), in South Asia (Faleiro 2006) and date palms, *Phoenix dactylifera* L. (Arecales: Arecaceae), in the Middle East (Mukhtar et al. 2011, Hussain et al. 2013, Hoddle et al. 2013, Hajjar et al. 2015). Recently, *R. ferrugineus* has spread to palm-growing Mediterranean (Vacas et al. 2013, Jalinas et al. 2015) and Caribbean (Roda et al. 2011) regions. Larvae feeding internally in the trunks can irreparably damage tissue and kill palms if left untreated (Murphy and Briscoe 1999). The full economic damage of *R. ferrugineus* is difficult to estimate because of its widespread geographic and host-plant range, but in the Sri Lanka coconut farming industry, for example, a recent estimate of

yearly damage is US\$16.6 million (Kings College London 2015). Nearly US\$26 million damage by this pest yearly has been estimated in date palm plantations in the Middle East (El-Sabea et al. 2009). Early identification of infestations in transported trees and offshoots is important for managing and limiting range expansion of this highly invasive species (Faleiro 2006, Al-Shawaf et al. 2013).

Acoustic methods have potential use for early detection of hidden *R. ferrugineus* larval infestations. Because the late instars are large and active, they are easily detected by a variety of insect acoustic detection systems (Al-Manie and Alkanhal 2005, Pinhas et al. 2008, Potamitis et al. 2009, Siriwardena et al. 2010, Rach et al. 2013). Even neonate *R. ferrugineus* are large enough to be detected

over distances of 0.5–1 m with sensitive equipment (Herrick and Mankin 2012).

Several different signal analysis methods have been developed to identify *R. ferrugineus* sounds and discriminate them from background noises (Mankin et al. 2008a, Pinhas et al. 2008, Potamitis et al. 2009, Rach et al. 2013). In an introductory study, Al Manie et al. (2003) and Al-Manie and Alkanhal (2005) described spectral features of *R. ferrugineus* detected in trunks of date palm trees in orchards near Al-Hasa, Saudi Arabia. It was noted that the peak signal energies of the *R. ferrugineus* sounds were between 6.5 and 20 kHz, while the peak energy of background noise was below 3.5 kHz. Acoustic testing has not been reported in the presence of wind, birds, and other important insect pests frequently encountered in date palm trees of the region, including *Oryctes elegans* Prell (Coleoptera: Scarabaeidae) (Bedford 1980, Khudhair et al. 2014, Al-Ayedh and Al Dhafer 2015). For this report, we assessed the capability of readily available acoustic detection and signal processing systems to detect *R. ferrugineus* in desert environmental conditions and discriminate its sounds from typical background noise in Saudi Arabian date palm orchards.

## Materials and Methods

### Recording Sites

Recordings were collected during April 2014 in two commercial orchards. The largest was in the Al Karj District (24° 13.57' N, 47° 14.77' E), 80 km south of Riyadh, Saudi Arabia, with ~2,500 *P. dactylifera* of various varieties and ages. Other crops, sheep, and birds were nearby, and farming or animal activities occasionally produced interfering background noise of interest in efforts to automate discrimination of targeted insect sounds from nontargeted signals. A smaller farm, near Al-Ghat (26° N, 44° 20' E), 250 km northwest of Riyadh, included various crops, camels, goats, birds, and several hundred *P. dactylifera*, as well as vehicles and equipment that produced diverse background noises.

### Recording and Verification Procedures

Records of 120 s each were collected over a 9-d period from 45 different trees and 33 offshoots in the southwest quadrant of the orchard at Al Karj, and from two trees during 1 d at Al Ghat. Multiple background noise samples, including bird and farm animal noise, were collected at both locations. Signals were monitored by listeners with headphones as they were recorded. One or more trees were selected randomly each day but, to reduce disturbance of uninfested, healthy trees, most of the sites tested each day at Al Karj were scouted earlier and visually assessed as unhealthy or potentially infested. Testing began approximately at daybreak, 0600 hours, and continued until after temperatures rose above 40°C, typically after 1030–1100 hours. As in Fiaboe et al. (2011), a 1.59-mm-diameter titanium drill bit was inserted near a site where infestation was suspected on the lower part of the tree or offshoot, and a 1.9-cm-diameter metal ferrule was clamped to the bit to widen its base. A sensor-preamplifier module (model SP-1L, Acoustic Emission Consulting [AEC] Inc., Sacramento, CA) was attached to the ferrule with a high force magnet (Model DMH-30, AEC Inc.). The signals were fed from the sensor module through an amplifier (AED-2010, AEC Inc.) to a digital audio recorder (Model PMD661, Marantz, Mahwah, NJ) at a 44.1-kHz digitization rate.

After recording, the vicinity of the recording site was inspected by removing the outer petiole or frond and dissecting the tissue underneath. The species and number of recovered larvae and adult

insects were noted along with information about wind and other background noise. At the Al Karj farm, we also used a global positioning system (nüvi 52, Garmin, Olathe, KS) to determine the tree coordinates.

### Insect Sound Impulse and Background Noise Analysis

Insect movement and feeding activity generates trains (groups) of 3- to 30-ms impulses (Potamitis et al. 2009, Mankin et al. 2011). The impulses within a train often have similar spectral characteristics because they are generated by the same mechanical processes. Because of these similarities, mean spectra (profiles) of multiple trains of verified insect sound impulses can be constructed and then matched by least-square comparisons with spectra of impulses in other recordings to assess whether the signals derive from insects (Mankin et al. 2011). The profiles are constructed using insect signal analysis programs such as DAVIS (Mankin et al. 2008a,b). Similar procedures can be used to screen out frequently occurring background noise. To test for potential differences among spectral and temporal patterns of sound impulses from *R. ferrugineus* and *O. elegans* in trunks and offshoots, we applied a three-stage assessment process adapted from methods developed previously in Mankin et al. (2008b).

First, the recordings were prescreened using Raven 1.5 software (Charif et al. 2008) to locate intervals relatively free of background noise that contained sounds originating from four specific insect-substrate conditions: *R. ferrugineus* larvae in 1) trunks and 2) offshoots, and *O. elegans* larvae in 3) trunks and 4) offshoots. Mean spectra of impulses recorded under each condition then were calculated using DAVIS, and designated as Rf-trunk, Rf-offshoot, Oe-trunk, and Oe-offshoot spectral profiles, respectively. In addition, the prescreening identified several types of noise that occurred frequently, including wind noise, birdsong, and machinery noise. Mean spectra (profiles) of intervals containing wind, two types of birdsong, and water pump noise were calculated to facilitate discrimination between insect sound impulses and background noise, as described in Mankin et al. (2008b) and below.

In the second stage of assessment, the spectrum of each sound impulse detected in all recordings was categorized by matching it against the four insect-substrate spectral profile types and the four background noise profiles using least-squares analysis in DAVIS (Mankin et al. 2011). Impulses classified as background noise were discarded.

Use of the profiles alone is not necessarily sufficient to discriminate insect sounds from background noise in wood substrates because tree tissues attenuate sound frequencies differentially as the signals travel to the sensors. Consequently, discrimination of insect sounds from background noise is more reliable when the temporal patterns of the signals are taken into account (Mankin et al. 2008a,b). In the third stage of analysis, the temporal patterns of sound impulses that matched the insect-substrate profile types were examined to verify whether they were similar to temporal patterns of previously validated insect sound impulses. Mankin et al. (2008a) reported that *R. ferrugineus* larvae often produce trains of at least 7 but fewer than 200 impulses separated by intervals <25 ms. Such trains, termed insect sound bursts, typically are detected only rarely at uninfested sites. A majority of trains containing >200 impulses that match insect-substrate profile types are recorded during periods when high levels of wind cause leaves to tap against each other. The tapping process sometimes produces short impulses with spectra that match those of impulses generated by feeding insects. To reduce the misclassification of wind-produced impulse trains as insect sound bursts, such trains are classified as background noise. The

rate of detected bursts in each recording,  $r_b$ , was calculated as an indicator of the likelihood of infestation at the recording site, designated as Low if  $r_b < 0.02 \text{ s}^{-1}$ , Medium if  $0.02 \text{ s}^{-1} \leq r_b < 0.06 \text{ s}^{-1}$ , and High if  $r_b \geq 0.06 \text{ s}^{-1}$ , as in (Mankin et al. 2008a).

### Statistical Analyses

Samples from the two farms were pooled for statistical analyses. The acoustically assessed likelihood of insect infestation in one sample collected at each recording site was compared with the observed presence or absence of infestation using Fisher's exact test (Proc freq; tables/fisher; SAS Institute 2013). Differences in the temporal patterns of sounds produced in offshoots where only *R. ferrugineus* and *O. elegans* had been recovered were assessed by comparing the mean number of impulses per burst and the mean total rate of impulses occurring in bursts using the Student 2-tail *t*-test with unequal variances. Measurements in trunks were not compared because recordings were obtained from only four trunks that contained *O. elegans* without *R. ferrugineus* also being present.

### Results

The range of environmental conditions encountered during the study provided ample opportunity to explore the general usability of the acoustic detection equipment in Saudi Arabian date palm orchards. Windy, dusty conditions were present on two of the eight days of recording, and tests were conducted at temperatures up to 42°C. No significant effects of these previously untested conditions were observed on the operability of the amplifier and recorder. Adults and larvae of both *R. ferrugineus* and *O. elegans* were present in many of the same trees, making it possible to collect recordings with different numbers of each or neither species present (Table 1) under varying conditions of wind, bird noise, and machinery noise.

Larval sound impulses detected in the study were heterogeneous in amplitude, duration, and spectral range, as seen in an oscillogram (Fig. 1A) and spectrogram (Fig. 1B) of 10 impulses matching insect–substrate profiles in a 0.1-s interval recorded from a tree where only *R. ferrugineus* larvae were recovered. Because of this heterogeneity, sound impulses produced by *R. ferrugineus* and *O. elegans* were not easily distinguished from each other. Examples of their similarities can be seen by comparing an oscillogram (Fig. 2A) and spectrogram (Fig. 2B) of typical impulse trains detected in an offshoot where only *R. ferrugineus* was found with the oscillogram (Fig. 2C) and spectrogram (Fig. 2D) of impulse trains in another offshoot where only *O. elegans* was found. Several trains containing at least 7 impulses with broad band energy over the range of 1–20 kHz (Fig. 2Ba–d, and Fig. 2De–g) appear in both oscillograms (Fig. 2Aa–d, and Fig. 2Ce–g), meeting criteria that qualified them as insect sound bursts (see below). One of the trains (Fig. 2Dh), however, contains impulses with strong energy only in the range of 1–7 kHz. Subsequent analysis, described below, characterized this as a train of bird calls.

**Table 1.** Distribution of *R. ferrugineus* (Rf) and *O. elegans* (Oe) across recording sites

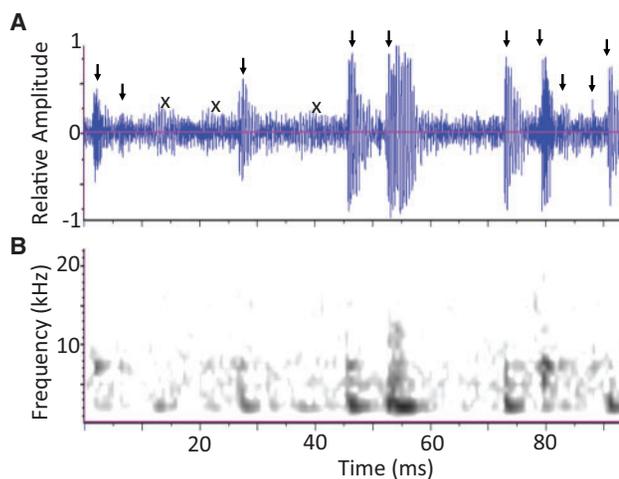
Species present	No. palm trunks	No. palm offshoots
Rf only	29	21
Oe only	4	7
Both Rf and Oe	9	5
Neither Rf nor Oe	3	–

### Discrimination of Insect Sounds and Background Noise

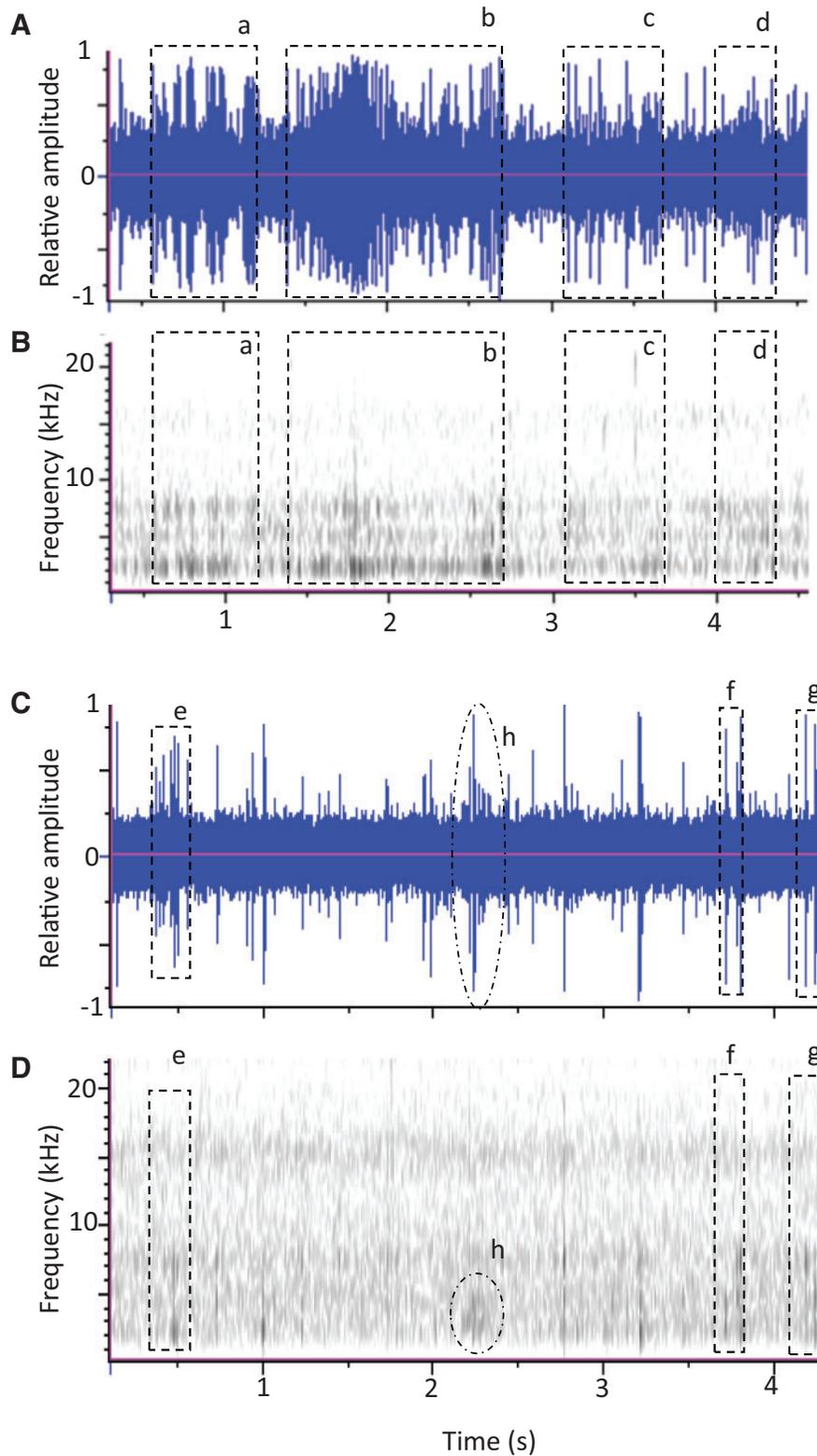
To ensure detectability of *R. ferrugineus* and *O. elegans* in trunks and offshoots, separate insect–substrate spectral profiles (Fig. 3A) were constructed from recordings in trunks and offshoots where either but not both were recovered after the acoustic recordings were collected. The profile labeled Rf–trunk was an average spectrum of 254 consecutive impulses recorded over a 63-s period in a palm tree trunk where only *R. ferrugineus* were recovered, and the Rf–offshoot profile was constructed from a series of 1,548 impulses recorded over a 30-s period in an infested offshoot. The Oe–trunk profile was constructed from a 13.97-s period of activity with 191 impulses recorded from a trunk containing only *O. elegans*, and the Oe–offshoot profile was constructed as an average of 198 impulses in a 14.64-s recording from an infested offshoot. All of the insect–substrate profiles were obtained from recordings containing minimal background noise.

It should be noted that adult *R. ferrugineus* and *O. elegans* were recovered only rarely without larvae nearby in the same tree. Previous studies with larvae and adults of another large beetle species, *Oryctes rhinoceros* (L.), indicate that movement and feeding activities of the larvae and adults of this beetle both produce sound impulses of similar spectral characteristics, possibly because they are generated by the same mechanical processes (Mankin and Moore 2010). In addition, preliminary analyses of signals collected from trees where only *R. ferrugineus* or *O. elegans* were recovered indicated that impulses matching all four constructed profiles—Rf–trunk, Rf–offshoot, Oe–trunk, and Oe–offshoot—were present in most recordings (including those in Figs 1 and 2). Because of the high variability in spectra of sounds produced by adults and larvae of both species, it was concluded that insect–substrate profiles could not be used alone to distinguish between *R. ferrugineus* and *O. elegans* sound impulses in trees or offshoots, nor could the profiles be used alone to distinguish between sounds of adults and larvae of each species in trees and offshoots. Therefore, we combined the counts of all insect sound bursts in each recording and estimated the rate of bursts,  $r_b$ , as the total count of bursts divided by the recording duration.

The background sounds most frequently encountered during recordings were wind, birds, and machinery noise, including irrigation



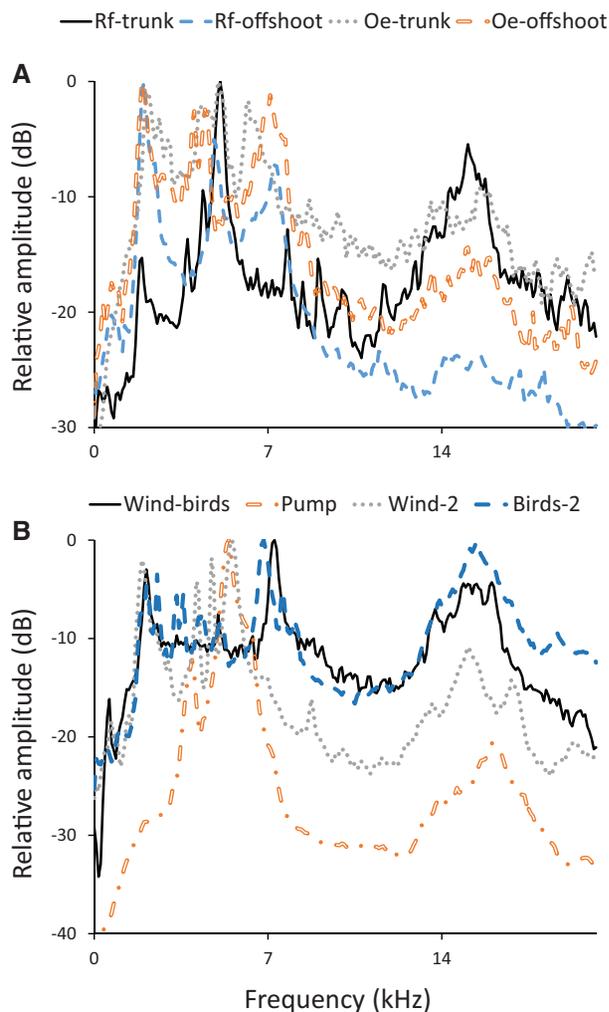
**Fig. 1.** Oscillogram (A) and spectrogram (B) of 10 impulses (each marked by an arrow) with heterogeneous amplitudes, durations, and spectra that met criteria for classification as insect sound impulses in a recording from a tree where *R. ferrugineus* larvae were recovered. Other signals (marked by an x) failed to meet the insect–substrate profile criteria. Darker shades in the spectrogram indicate frequencies of higher energy at the specified time.



**Fig. 2.** Oscillograms (A, C) and spectrograms (B, D) of signals produced in offshoots by *R. ferrugineus* and *O. elegans*, respectively. Signals enclosed by dashed boxes indicate bursts of (a) 74, (b) 185, (c) 27, and (d) 17 *R. ferrugineus* impulses, and (e) 11, (f) 7, and (g) 7 *O. elegans* impulses. Signals enclosed by dot-dashed oval (h) indicate a bird call. Darker shades in the spectrograms indicate frequencies of higher energy at the specified time.

pumps. Four profiles were constructed to help screen out intervals when these sounds interfered with insect detection. A profile labeled Wind-birds (Fig. 3B) was constructed as an average spectrum of signals recorded from a trunk during 11.51 s of wind gusts and bird

noise. A profile representing birdsong of a different species, Birds-2, was constructed from 9.99 s recorded when singing birds were flying overhead. Signals containing wind gusts recorded over 14.07 s from a trunk were used to construct the Wind-2 profile. Signals recorded



**Fig. 3.** Mean spectra (profiles) of (A) sound impulses detected in palm trunks and offshoots at recording sites where only *R. ferrugineus* were found (Rf-trunk and Rf-offshoot, respectively), and sound impulses detected in palm trunks and offshoots at recording sites where only *O. ferrugineus* were found (Oe-trunk and Oe-offshoot, respectively); and (B) background noise signals recorded during periods with noticeable wind, farm animal, and bird calls (labeled Wind-birds, Birds2, Wind-2) and during operation of an irrigation pump (Pump).

over 11 s from a trunk near a running irrigation pump were used to construct a profile of low-frequency engine noise, Pump. It should be noted that the sound pressure levels of the background noise was up to 20 dB greater than for the insect sounds, which is reflected in a greater range of relative amplitude (40 vs. 30 dB). As detailed in the Methods above, the profiles were matched by the DAVIS program to the spectrum of each sound impulse detected in the recordings to classify it as either an insect sound impulse or as background noise. Trains with at least 7 insect sound impulses but fewer than 200 were classified by DAVIS as insect sound bursts.

#### Detectability of *R. ferrugineus* in Date Palm Orchards

Because most of the recording sites had been scouted as potentially infested the previous day, most were found to be infested with either or both *R. ferrugineus* or *O. elegans* when they were checked for dissected tissue, fresh sawdust, and live or dead larvae or adults after the recordings were conducted. In addition, because the distances between the sensor locations and any insects present in offshoots

**Table 2.** Distribution of computer-assessed infestation likelihoods at recording sites in trunks that were uninfested or infested with *R. ferrugineus*

Computer-assessed infestation likelihood	No. sites	
	Infested	Uninfested
Low ( $r_b < 0.02 \text{ s}^{-1}$ )	3	3
Medium ( $0.02 \text{ s}^{-1} \leq r_b < 0.06 \text{ s}^{-1}$ )	4	0
High ( $r_b \geq 0.06 \text{ s}^{-1}$ )	22	0

$P = 0.0048$  that assessment is independent of the presence or absence of infestation (Fisher exact test, table probability  $P = 0.004$ ,  $n = 32$ ).

usually were shorter than their distances in the trunk, the movement and feeding activities of either *R. ferrugineus* or *O. elegans* in offshoots often could be detected more easily than in the trunks of 30-cm or larger diameter trees. To estimate the detectability of *R. ferrugineus* in trunks of larger trees, we counted the numbers of trees where only *R. ferrugineus* or no insects were found, and compared the results with computer assessments of infestation likelihood for the same trees (Table 2). The three trees where no *R. ferrugineus* were found and three infested trees were assessed at Low likelihood of infestation ( $r_b < 0.02 \text{ s}^{-1}$ ), but all other trees were assessed at Medium or High likelihood of infestation. At Al Karj, trees infested with *O. elegans* were clumped together in one small area (Fig. 4). Trees infested with *R. ferrugineus* also were observed in clumps, but were distributed widely through the orchard.

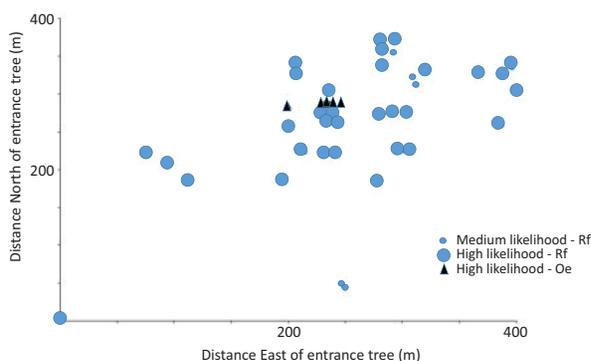
#### Temporal Pattern Differences Between Impulses in *R. ferrugineus* and *O. elegans* Bursts

As recordings were collected at different trees, it was noticed that the bursts of sound impulses detected at sites where only *O. elegans* was found often seemed shorter in duration than those where only *R. ferrugineus* was found. A Student 2-tail  $t$ -test with unequal variances indicated that the mean number of impulses per burst was significantly higher in recordings in offshoots where only *R. ferrugineus* were found compared with recordings in offshoots where only *O. elegans* was found ( $P = 0.016$ ; Table 3). A significant difference also was found in the mean rates of impulses that occurred within bursts detected in offshoots where only *R. ferrugineus* or *O. elegans* were found ( $P = 0.001$ ).

#### Discussion

This survey of sounds recorded in Saudi Arabian date palm orchards provided useful information about features needed in an automated surveillance system that could assist managers in controlling *R. ferrugineus* populations. Characterization of the composition and magnitude of different types of background noise was of particular interest because bird and farm animal noise, wind noise, and machinery noise usually have spectral characteristics that must be discriminated from target insect sounds differently in different agricultural (Mankin et al. 2009, Sanders et al. 2011) and urban (Mankin and Moore 2010, Fiaboe et al. 2011) environments. As in Al-Manie et al. (2003) and Al-Manie and Alkanhal (2005), much of the background noise had peak frequencies below 3.5 kHz (Fig. 2B). Some bird and wind noise occurred at higher frequencies but could be discriminated from *R. ferrugineus* signals by the occurrence of multiple frequency harmonics and differences in the temporal patterns of sound impulses.

It was of interest to consider methods of distinguishing sounds produced by *R. ferrugineus* from those produced by a



**Fig. 4.** Distribution of *R. ferrugineus* and *O. elegans* infestations acoustically detected and visually confirmed at Al Karj farm: Large dots—acoustic classification of high infestation likelihood with visual confirmation of *R. ferrugineus*; small dots—acoustic classification of medium infestation likelihood with visual confirmation of *R. ferrugineus*; triangles—acoustic classification of high infestation likelihood with visual confirmation of *O. elegans*. Distance is relative to position of tree near entrance at southwest corner of property.

**Table 3.** Measurements of *R. ferrugineus* ( $n=21$ ) and *O. elegans* ( $n=7$ ) sound impulse temporal patterns (mean  $\pm$  SE) in palm offshoots

Measurement	<i>R. ferrugineus</i>	<i>O. elegans</i>	<i>t</i>	<i>P</i>
No. impulses / burst	44.4 $\pm$ 9.6	18.3 $\pm$ 2.9	2.60	0.016
Total no. burst impulses $s^{-1}$	11.5 $\pm$ 3.0	2.51 $\pm$ 1.0	2.85	0.001

Values of *t* and *P* were calculated from Student 2-tail *t*-test with unequal variances, *df* = 23.

frequently co-occurring nontarget insect, *O. elegans*. The signals are similar enough in spectral characteristics that they cannot be distinguished easily by spectra alone (Fig. 1), but the sound impulses produced by these two species differed in temporal pattern (Table 3). As in measurements obtained from healthy (control) *R. ferrugineus* larvae in Jalinas et al. (2015), the mean number of impulses per burst for *R. ferrugineus* was observed to be  $>30$ , but was only 18 for *O. elegans*. The mean total rate of impulses occurring within bursts was greater than  $10 s^{-1}$  for *R. ferrugineus* compared with the mean of  $2.51 s^{-1}$  for *O. elegans*. Both *R. ferrugineus* and *O. elegans* are significant pests in this case, but in general, there is potential value in developing further the capability to distinguish acoustically between target and nontarget insects. Because temperature and instar can affect the level of insect activity (Mankin et al. 2011), further studies are needed to determine whether such factors strongly affect the rates of impulses within sound bursts produced by the two species.

For practical reasons, it was of interest to consider whether there were differences in sounds produced by *R. ferrugineus* in trunks and offshoots. It was determined that the same spectral patterns can be used to identify larvae in both environments, but larvae are easier to detect in offshoots due the shorter distances and lower signal distortion between the larvae and the sensors.

The distribution patterns of both *R. ferrugineus* and *O. elegans* in the Al Karj orchard (Fig. 3) appeared to have strong spatial dependence, as has been frequently observed for other pest insects (Liebhold et al. 1993, Mankin et al. 2007). Consequently, there is potential to reduce the costs of chemical and biological control by use of monitoring tools that enable targeting of infestations.

Experience with the currently available insect acoustic detection technology suggests it is robust enough for short-term use to assist

visual surveys in the orchards, but that better-sealed instruments would be preferable for long-term monitoring. In addition, greater automation and more simplified operating procedures would enable more persons to use the technology in their research and surveillance programs. Microcontroller systems already under development for use in *R. ferrugineus* detection, e.g., Rach et al. (2013), and those already in use for real-time processing of insect communication signals (Mankin et al. 2013) show considerable promise as platforms for development of simpler, more automated detection systems. Such systems can operate under harsh conditions that are uncomfortable for scouts, and scouts with expertise to recognize *R. ferrugineus* infestations may not be readily available.

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