Acoustic Detection of Melolonthine Larvae in Australian Sugarcane

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ABSTRACT Decision support systems have been developed for risk analysis and management of root-feeding white grubs (Coleoptera: Scarabaeidae: Melolonthinae) in Queensland, Australia, sugarcane (*Saccharum* spp.), based partly on manual inspection of soil samples. Acoustic technology was considered as a potential alternative to this laborious procedure. Field surveys were conducted to detect the major pests *Dermolepida albohirtum* (Waterhouse) near Mackay, and *Antitrogus parvulus* Britton near Bundaberg. Computer analyses were developed to identify distinctive scrapes and other sounds produced by *D. albohirtum* and *Antitrogus* species and to distinguish them from sounds of nondamaging white grubs (Rutelinae, Dynastinae), as well as from extraneous, wind-induced tapping signals. Procedures were considered for incorporating acoustic methods into surveys and sequential sampling plans. Digging up and inspecting sugarcane root systems requires 10–12 min per sample, but acoustic assessments can be obtained in 3–5 min, so labor and time could be reduced by beginning the surveys with acoustic sampling. In a typical survey conducted in a field with low population densities, sampling might terminate quickly after five negative acoustic samples, establishing a desired precision level of 0.25 but avoiding the effort of excavating and inspecting empty samples. With a high population density, sampling might terminate also if signals were detected in five samples, in which case it would be beneficial to excavate the samples and count the white grubs. In intermediate populations, it might be necessary to collect up to 20 samples to achieve desired precision, and acoustic methods could help determine which samples would be best to excavate.

KEY WORDS *Antitrogus parvulus*, *Antitrogus consanguineus*, *Dermolepida albohirtum*, *Lepidiota*, acoustic detection

Melolonthine (Coleoptera: Scarabaeidae) white grubs cause considerable economic damage to sugarcane (*Saccharum* spp.) in Australia, with greatest damage by *Dermolepida albohirtum* (Waterhouse) and *Lepidiota frenchi* Blackburn in central and northern Queensland, and by *Antitrogus parvulus* Britton, *Antitrogus consanguineus* (Blackburn), and *Lepidiota negatoria* Blackburn in the Bundaberg region of southern Queensland (Robertson et al. 1995, Agnew 1997). The larvae destroy the roots of the sugarcane stool, an underground mass of stalks with viable buds from which sugarcane stalks develop. Heavy attack may result in death of the sugarcane stalk, and the stool may be pulled out of the ground during harvest, creating gaps in the vegetation (Agnew 1997).

Severe outbreaks of *D. albohirtum* in northern Queensland beginning in the early 1990s (Robertson et al. 1995) prompted efforts to forecast (Horsfield et al. 2008) and control white grub populations in sugarcane fields. A management program, GrubPlan, was subsequently extended to growers (Hunt et al. 2002, 2003). Growers were advised to monitor their fields for current infestations and to maintain awareness of the infestation patterns in nearby fields to help decide the best mix of larval control options for different sugarcane fields each year (Samson et al. 2005). Options available to growers include controlled-release formulations of chlorpyrifos and imidacloprid (suSCon Blue and suSCon Maxi, respectively; Crop Care Australasia) for application at or soon after planting ("plant crops"). These treatments remain effective for 2–3 crop years. In areas with lower risk of infestation, several suspension concentrate formulations of imidacloprid (various product names and companies) are available for application to plant crops and to regenerating cane after harvest ("ratoon crops"). For ratoon crops, other options include plow-out or rotation cropping when high white grub infestations are expected to reduce productivity. In very low-risk environments, an option is to delay treatment until annual monitoring determines that white grub populations have begun to develop.

The most widely available method for surveying the fields is to excavate and inspect sugarcane plants and stools (Southwood 1969). With high populations of

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white grubs, assessments of infestation risk can be obtained with as few as five samples, but with intermediate, scattered populations, 20 or more samples may be needed, consistent with sequential sampling at precision levels of 0.1–0.25 (Allsopp and Bull 1989). Growers are not eager to use such time-consuming, difficult, and destructive methods when white grub populations are perceived as low. Nevertheless, because crop growth patterns prevent entry to the crop at the time of highest white grub populations, it is preferable to implement preemptive management strategies before irreversible damage occurs.

Alternative, less time-consuming methods are under consideration for conducting surveys, including acoustic technology, which had been applied previously to detect other white grubs (Mankin et al. 2000, 2007) and other beetle species (Mankin et al. 2008a,b; Pinhas et al. 2008). We conducted an acoustic detection study to determine whether *D. albohirtum*, *Antitrogus* spp., and *Lepidiota* spp. could be detected readily at different field locations where each was prevalent. It was of interest also to identify signal features that may be present when a sample site contains root-feeding Melolonthinae, but absent when the sample contains only ruteline or dynastine white grubs that are found in sugarcane fields but are not usually significant pests (Richter 1958, Logan 1999).

Materials and Methods

Acoustic Instruments, Signal Recording, and Soil Sampling Procedures. Recordings were collected for periods of 3 min or longer at 27 sample sites in commercial sugarcane fields near the BSES Limited experiment station at Mackay, and 31 sample sites in commercial or experiment station fields near Bundaberg between 23 April and 3 May 2007. Air temperatures during recording periods ranged from ≈25 to 33°C. One or more 30-cm nails were inserted into the cane stool or nearby soil to serve as signal waveguides. At several sample sites, the waveguides were moved to different nearby positions for additional recordings.

Two different portable acoustic systems were used to detect subterranean vibrations, an accelerometer (model 4370, Brüel and Kjær [B&K], Nærum Denmark) connected to a charge amplifier (model 2365, B&K), as in Mankin et al. (2000, 2001, 2002), and a sensor-preamplifier module (model SP-1, Acoustic Emission Consulting [AEC], Inc., Sacramento, CA) connected to an amplifier unit (model AED-2000, AEC), as in Mankin and Lapointe (2003) and de la Rosa et al. (2008). The sensors were attached magnetically to the waveguides. Signals were stored on a dual-channel, digital audio recorder (model HD-P2, Tascam, Montebello, CA) sampling at 44.1 kHz (24 bits), and subsequently copied to a computer for digital signal analyses.

With all recordings, care was taken to protect the wires and sensors from contact with leaves, stalks, or other objects. Extraneous sources of noise were noted. Recordings could be monitored with headphones as they were being collected, which enabled troubleshooting of instrumentation or background noise problems. To provide protection and ease of use in dense stands of sugarcane, the accelerometer system was carried in a plastic tray that had been bolted to a short plastic stool. The AED-2000 was more portable than the accelerometer system, and could be carried by hand through the densest stands. An umbrella was used in sunny areas to protect the instruments from overheating.

After all recordings were completed, the soil at the waveguide was excavated and sound-producing organisms were hand-sorted from the sample. The minimum excavated volume was approximately the dimensions of a 30-cm cube, based on the expected range of detectability (Zhang et al. 2003b), and the largest was approximately twice that volume. These 30–40-cm-cube volumes, centered on sugarcane stools, are the usual sampling size for estimating numbers of white grubs in Australian canefields.

Damaging melolonthine white grubs were identified to species by their raster pattern (Agnew 1997). However, *L. frenchi* and *L. negatoria*, which both occur near Mackay, have the same raster pattern and cannot be separated by this method (Agnew 1997). Usually, *L. frenchi* is the predominant species in this region and samples containing either species were specified as *L. frenchi* for simplicity.

Listener Assessment of Infestation Likelihood. The capability to use acoustic technology in field surveys of subterranean insect populations stems partly from occurrences of spectrally distinctive, 3–10-ms sound impulses produced during insect movement and feeding activities (Mankin et al. 2000; Zhang et al. 2003a,b; Mankin et al. 2007), detected only rarely when insects are absent. Such signals are easily identified and discriminated by digital signal processing software (see below) and also by listeners with headphones. Because most listeners have previous experience in identifying human vocalizations (Aaronson et al. 2009) or other sounds of interest (Best et al. 2005) in noisy backgrounds, they need only ≈10–20 min of training in comparisons between insect sound impulses and background noises to identify the spectral and temporal patterns that typically distinguish insect-produced sound impulses from other signals. One or more persons monitored the headphones at each recording site (see Acknowledgments), and listener assessments of infestation likelihood were assigned as in Mankin et al. (2007), where l_{ow} indicates no insect-produced (valid) sounds or only a few faint sounds during a recording period, m_{edium} indicates sporadic or faint groups of valid sounds, and h_{igh} indicates frequent, easily detectable groups of valid sounds.

A series of recordings from 13 different sample sites in one sugarcane field was obtained using the AED-2000 to consider how rapidly a field could be surveyed using listener assessment methods. The recordings were conducted for 2-min intervals, whereas the sounds were monitored by a panel of three listeners (see Acknowledgments). The infestations at these sites were assessed by excavation, 2–4 d subsequently. *Antitrogus* spp. and *L. negatoria* were the major pest

insects excavated in this experiment, and their numbers were combined for analyses of infestation likelihood.

Digital Signal Processing and Classification. Initial screening of recordings was performed using Raven 1.3 software (Charif et al. 2008), which enabled replay of audio simultaneously with amplitude-time (oscillogram) and frequency-time (spectrogram) displays. To reduce low- and high-frequency background noise, the accelerometer signals were band-pass filtered between 0.2 and 5 kHz (occasionally between 0.2 and 8 kHz). The AED-2000 signals were band-pass filtered between 1 and 5 kHz because the amplifier itself filters out signals below 1 kHz (Mankin and Lapointe 2003). The screenings indicated that individual impulses and groups (trains) of impulses were important signal features in these recordings, and much of the analysis described below was conducted for their characterization. A subclass of trains containing impulse counts within a delimited range, denoted as bursts (Mankin et al. 2008b), were of particular interest as a means of distinguishing insect sounds from background noise because such trains occurred more frequently when insects were present than when absent.

Spectral patterns of impulses and temporal patterns of impulse trains were analyzed with a custom-written signal processing program, DAVIS (Digitize, Analyze, and Visualize Insect Sounds, Mankin 1994, Mankin et al. 2000), discarding long-duration, low frequency signals that comprise most background noise (Mankin et al. 2007, 2008a,b). The spectrum of each impulse was compared against a set of averaged spectra (see Spectral Profiles below) of white grub sounds or impulsive, cane-tapping background noises. Impulses were discarded if their spectra failed to match any of the white-grub profiles in the set within an empirically determined difference threshold, T_s (Mankin et al. 2008b), or if they matched the background noise profile more closely than any white grub profile. Because the accelerometer and AED-2000 had different spectral sensitivities at different frequencies (Mankin et al. 2003), recordings from the two instruments were analyzed separately, and different sets of spectral profiles were constructed from impulses detected by each instrument.

Spectral Profiles. An objective of the study was to identify and discriminate sound impulses produced by two target insects, *D. albohirtum* and *A. parvulus*, and much of the signal analysis was focused on the spectral characteristics of sound impulses produced by these two species. Initially, spectral profiles were constructed from *D. albohirtum* (*albo*) sound impulses recorded by accelerometer at sample sites where these were the only insects recovered (see *Results*). The profiles were constructed as an average spectrum of a series of consecutive impulse trains (Mankin 1994, Mankin et al. 2000), independently validated as insect sounds in Raven. These profiles did not match well with signals produced by *A. parvulus* in recordings near Bundaberg, so a second (*parv*) profile was constructed from recordings at sample sites where only *A. parvulus* were recovered. To facilitate discrimination of insect sounds from background noise, spectral profiles also were constructed by averaging the spectra of leaf- or stem-tapping impulses that occurred during light wind. Ultimately, two sets of spectral profiles were assembled, one for use with accelerometer recordings (see *ACC-albo*, *ACC-parv*, and *ACC-leaf taps* in Results), and one for AED-2000 recordings, including *AED-albo* and *AED-leaf taps.*

Temporal Pattern Analyses. Previous studies of insect sound-impulse temporal patterns (Mankin et al. 2008 a,b) suggested that analysis of the timing of impulses and groups of impulses could help predict the absence or presence of infestations, so the occurrence times of valid impulses were saved in an impulse-sequence. Each impulse was labeled to indicate its best-matching spectral profile. It should be noted that, because the sounds were of different amplitudes (e.g., Fig. 1), all spectral comparisons were performed after the spectra had been normalized by referencing the acceleration, A, at each frequency to the maximum acceleration, A_{max}, in the 0.2–5-kHz reference range (Mankin and Benshemesh 2006), i.e., $\mathrm{dB} = 20 \log_{10}(A/A_{max})$.

The temporal patterns of impulses were analyzed by first calculating their interpulse intervals and then combining together groupings of impulses that listeners tended to classify as separate sounds, typically groups (trains) of impulses separated by intervals $<$250 ms (Mankin et al. 2008b). The beginning and ending times of impulse trains, and the number of impulses per train, n_t, were stored in separate, train-sequence spreadsheets for each recording. Each train was labeled to indicate the spectral profile matched most frequently by the impulses in that train.

The train-sequence spreadsheets were analyzed to determine the distributions of impulse counts typically found in trains produced by *D. albohirtum* or *A. parvulus*, to estimate a delimited range of impulse counts, denoted as a burst, which would be most indicative of an insect sound. Based on the distributions of impulse counts, n_t, in trains detected by accelerometer when only *D. albohirtum* occurred at a sample site, lower, $n_{l\text{-}albo}$, and upper, $n_{u\text{-}albo}$, cut-off counts were estimated for trains with impulses that matched most frequently with the *ACC-albo* profile. The *ACC-albo* trains with counts intermediate between the cut-offs were identified as *ACC-albo* bursts. Similarly, based on the distributions of n_t when only *A. parvulus* occurred at a sample site, lower, $n_{l\text{-}parv}$, and upper, $n_{u\text{-}parv}$, cut-off counts were estimated for trains with impulses that matched most frequently with the *ACC-parv* profile. The *ACC-parv* trains with counts intermediate between the cut-offs were identified as *ACC-parv* bursts. Because the timing of impulses within trains was similar for both the AED-2000 and the accelerometer, the lower and upper cut-off counts for the AED-2000 bursts were estimated as $n_{l\text{-}albo}$ and $n_{u\text{-}albo}$, respectively, for recordings near Mackay, and $n_{l\text{-}parv}$ and $n_{u\text{-}parv}$, respectively, for recordings near Bundaberg.

Using the estimated cut-off counts above, we reexamined the signals in the complete set of accelerom-

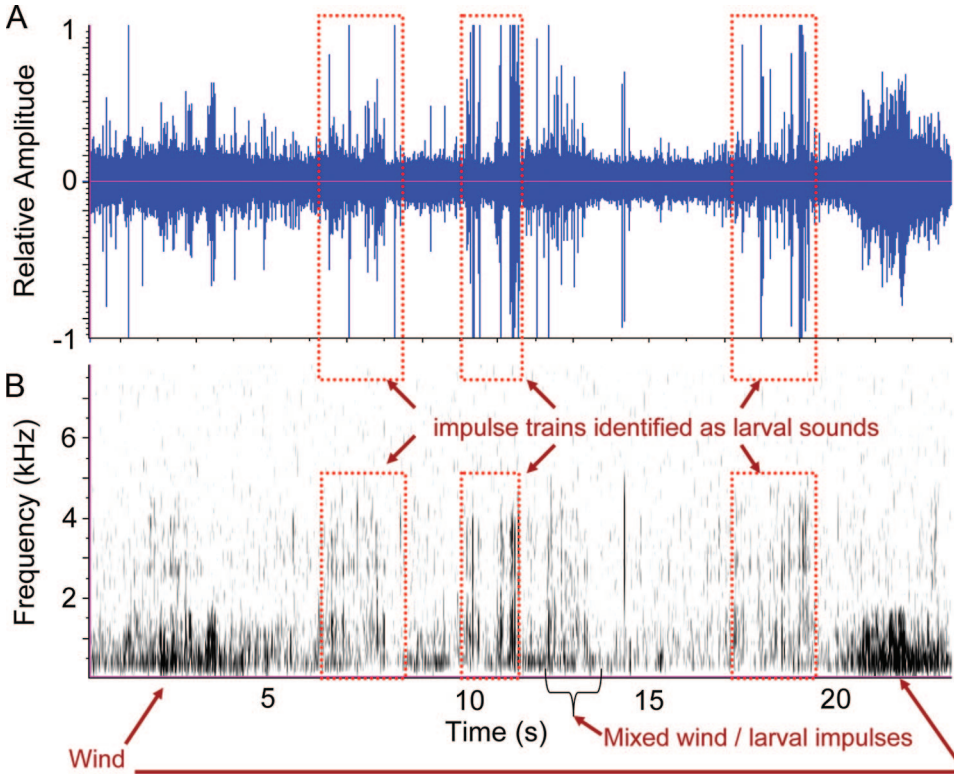

Fig. 1. Oscillogram (A) and spectrogram (B) of signals recorded by accelerometer from *D. albohirtum* larvae moving and feeding in the root system of a sugarcane plant in a field near Mackay. Signals enclosed by dotted lines indicate groups of impulses (trains) that were classified by computer analyses and by listeners as insect sounds. Low-frequency noise from two gusts of strong wind is marked during the first 5 s and last 3 s of the 23-s record. Darker shades in the spectrogram indicate frequencies with higher signal energy at the specified time. (Online figure in color.)

eter recordings collected near Mackay, and calculated the rates (number/min) of *ACC-albo* trains and bursts, $r_{ACC\text{-}albo\text{-}t}$, and $r_{ACC\text{-}albo\text{-}b}$, respectively. Rates of *ACC-parv* trains and bursts, $r_{ACC\text{-}parv\text{-}t}$ and $r_{ACC\text{-}parv\text{-}b}$, respectively, were calculated for signals in all accelerometer recordings collected near Bundaberg. Similar calculations were performed for rates of trains and bursts that matched the *AED-albo* profile, $r_{AED\text{-}albo\text{-}t}$ and $r_{AED\text{-}albo\text{-}b}$, respectively. Pairwise correlations among numbers of organisms of different types and the rates of *ACC-albo*, *ACC-parv*, and *AED-albo* trains and bursts at different sample sites were analyzed using JMP 4.0.2 (Sall et al. 2001).

Computer-Rated Likelihood of Infestation. We hypothesized that the likelihood of infestation of samples by *D. albohirtum* near Mackay and *A. parvulus* near Bundaberg could be estimated by constructing indicators (Mankin et al. 2007) based on the rates of trains or bursts detected, with the indicator value set to l_{ow} if the rate was below a lower cut-off, $r_{lower\text{-}t}$ or $r_{lower\text{-}b}$, for trains/min or bursts/min, respectively, h_{igh} if the rate exceeded an upper cut-off, $r_{upper\text{-}t}$ or $r_{upper\text{-}b}$, and m_{edium} if the rate was intermediate between the two cut-offs. The cut-off-rate values were estimated from the observed distributions of rates of *D. albohirtum* and *A. parvulus* trains and bursts near Mackay and Bundaberg, respectively (see below). The distributions of l_{ow}, m_{edium}, and h_{igh} likelihoods of infestation were compared for infested and uninfested samples using the Wilcoxon two-sample exact test (Proc NPAR1WAY, SAS Institute 2004) under the null hypothesis that the distributions of the likelihood indicator values were independent of infestation presence or absence. Consequently, a probability, $P < 0.05$, would indicate that the distributions of computer-rated likelihood indicator values were significantly different for infested and uninfested samples.

Results

At all sample sites, multiple sound impulses were detected that had amplitudes and durations similar to those in signals recorded previously from white grubs (Mankin et al. 2000, Zhang et al. 2003a) and other subterranean insects (Mankin et al. 2001, 2002). Listeners assessed all sample sites at either m_{edium} or h_{igh} likelihood of insect infestation (see Assessed likelihood columns in Tables 1–3), and the samples all contained at least one sound-producing organism. However, only approximately half of the organisms recovered near Mackay were considered sugarcane pests, including 63 *D. albohirtum* and *L. frenchi* root-

Table 1. Numbers of organisms recovered at sample sites near Mackay, listener assessments of infestation likelihood, and rates of *ACC-albo* trains and bursts, arranged in order of numbers of *D. albohirtum* recovered

No. organisms recovered				Assessed likelihood	Rate (no./min) of	
Dalb.[a]	Lfre.[b]	Rtl.[c]	Other[d]		Trains[e]	Bursts[f]
8	0	0	0	high	21.56	14.85
7	0	0	0	high	2.33	0.74
5	0	0	1	high	6.65	2.89
5	0	2	1	high	1.16	0.58
3	0	0	0	medium	15.34	9.61
3	0	0	0	high	17.38	8.19
3	0	5	1	high	9.31	4.79
3	0	1	0	medium	23.00	2.59
3	0	0	5	high	0.00	0.00
3	0	4	1	high	0.26	0.00
3	0	0	1	high	0.00	0.00
2	0	0	0	high	18.15	15.35
2	0	1	0	high	19.52	9.43
2	0	0	0	high	28.15	6.28
2	0	0	1	medium	0.29	0.29
1	0	0	0	medium	7.54	2.69
1	0	1	8	high	3.25	1.68
1	0	1	0	medium	3.61	1.29
1	0	4	0	high	1.92	0.82
1	0	0	2	high	1.69	0.56
1	0	0	2	high	1.16	0.29
1	0	1	0	high	0.26	0.00
1	0	0	0	medium	0.00	0.00
1	0	0	0	medium	0.33	0.00
0	1	0	3	high	0.80	0.00
0	0	0	3	medium	0.94	0.16
0	0	1	0	medium	0.32	0.00

[a] *D. albohirtum.*
[b] *L. frenchi* (or *L. negatoria,* see Materials and Methods).
[c] Rutelinae spp., including *Anop. parvulus* and *Anop. boisduvalii,* and *Anomala* spp.
[d] Including *Dasygnathus* spp., mole crickets, tenebrionids, cockroaches, earthworms, centipedes, and cane toads.
[e] $r_{ACC\text{-}albo\text{-}t}$ = no./min of trains containing a plurality of impulses that matched the *ACC-albo* profile (see Fig. 4), where trains are groups of impulses distinguishable as distinct sounds (interpulse intervals <250 ms) (see Materials and Methods under Temporal Pattern Analyses).
[f] $r_{ACC\text{-}albo\text{-}b}$ = no./min of *ACC-albo* trains with $2 < n_t < 51$ impulses per train (see Materials and Methods under Temporal Pattern Analyses).

Table 2. Numbers of organisms recovered at sample sites near Bundaberg, listener assessments of infestation likelihood, and the rates of *ACC-parv* trains and bursts, arranged in order of numbers of *Antitrogus* recovered

No. organisms recovered				Assessed likelihood	Rate (no./min) of	
Antitr.[a]	Lcri.[b]	Rtl.[c]	Other[d]		Trains[e]	Bursts[f]
12	0	0	2	high	86.332	3.302
9	6	0	2	high	21.439	6.267
6	0	0	0	high	5.685	4.91
6	0	0	1	high	11.838	0
5	0	0	5	high	64.482	27.77
5	24	0	3	high	44.76	8.805
5	0	0	1	medium	3.486	1.409
4	0	0	0	high	21.245	10.503
2	20	1	0	high	18.879	4.72
2	0	0	1	high	7.256	3.155
2	0	0	0	high	24.082	0.33
1	0	5	1	high	12.196	2.832
0	0	0	5	medium	6.726	0.928
0	0	0	1	medium	12.712	4.926
0	0	0	1	medium	6.469	1.318
0	25	0	0	high	3.918	0.28
0	22	0	0	high	1.958	0
0	0	0	2	medium	0.324	0

[a] *A. parvulus,* and *A. consanguineus.*
[b] *L. crinita.*
[c] Rutelinae spp., including *Anop. porosus* and *Anop. boisduvalii.*
[d] Including dynastines, wireworms, cane toads, cockroaches, earthworms, centipedes, ants, and chinch bugs.
[e] $r_{ACC\text{-}parv\text{-}t}$ = no./min of trains containing a plurality of impulses that matched the *ACC-parv* profile (see Fig. 4), where trains are groups of impulses distinguishable as distinct sounds (interpulse intervals <250 ms) (see Materials and Methods under Temporal Pattern Analyses).
[f] $r_{ACC\text{-}parv\text{-}b}$ = no./min of *ACC-parv* trains with $4 < n_t < 51$ impulses per train (see Materials and Methods under Temporal Pattern Analyses).

feeding larvae (Table 1). Other recovered organisms included rutelines, *Anoplognathus parvulus* Waterhouse, *Anoplognathus porosus* (Dalman), *Anoplognathus boisduvalii* Boisduval, and *Anomala* spp. (21 larvae, Table 1), as well as dynastines (*Dasygnathus* spp.) and various ants, cockroaches, tenebrionids, centipedes, earthworms, and cane toads (30 organisms; see Other, Table 1). Approximately 80% of the organisms recovered near Bundaberg were considered sugarcane pests, primarily *A. parvulus* (42 larvae), *A. consanguineus* (Blackburn) (17 larvae), and *Lepidiota crinita* Brenske (97 larvae) (Table 2). Other recovered organisms included *Anop. boisduvalii,* and *Anop. porosus* (six larvae), and various ants, cockroaches, wireworms, centipedes, chinch bugs, crickets, wireworms, and cane toads (25 organisms). Given that 20–50% of the recovered organisms would not usually be targeted as pests, we considered potential analyses that might discriminate targeted sugarcane pests from other sound producers to avoid assessing recording sites as infested when they did not contain pests.

An approach to separately identifying *D. albohirtum* larvae was suggested from listener assessment and signal processing of sounds at recording sites where only these larvae were recovered (for an example, see Fig. 1. The example begins with a wind gust followed by two groups (trains) of impulses that listeners identified as distinctive larval scraping sounds (marked by dotted boxes). Immediately after the second impulse train, there is a period of larval impulses embedded in wind noise, followed by a third train identified as a larval sound, and a final wind gust.

The three marked impulse trains in this example were easily identified and distinguished from wind using the DAVIS insect-signal processing program (Mankin 1994, Mankin et al. 2000). The spectra and time courses of the impulses within the distinctive trains were relatively consistent (Fig. 2), and such signals were abundant in recordings at many of the sample sites when *D. albohirtum* was recovered. The frequent occurrence of such signals suggested that they might have spectral and temporal patterns that could indicate the presence of *D. albohirtum* larvae, as had been observed previously for other insects (Mankin et al. 2007).

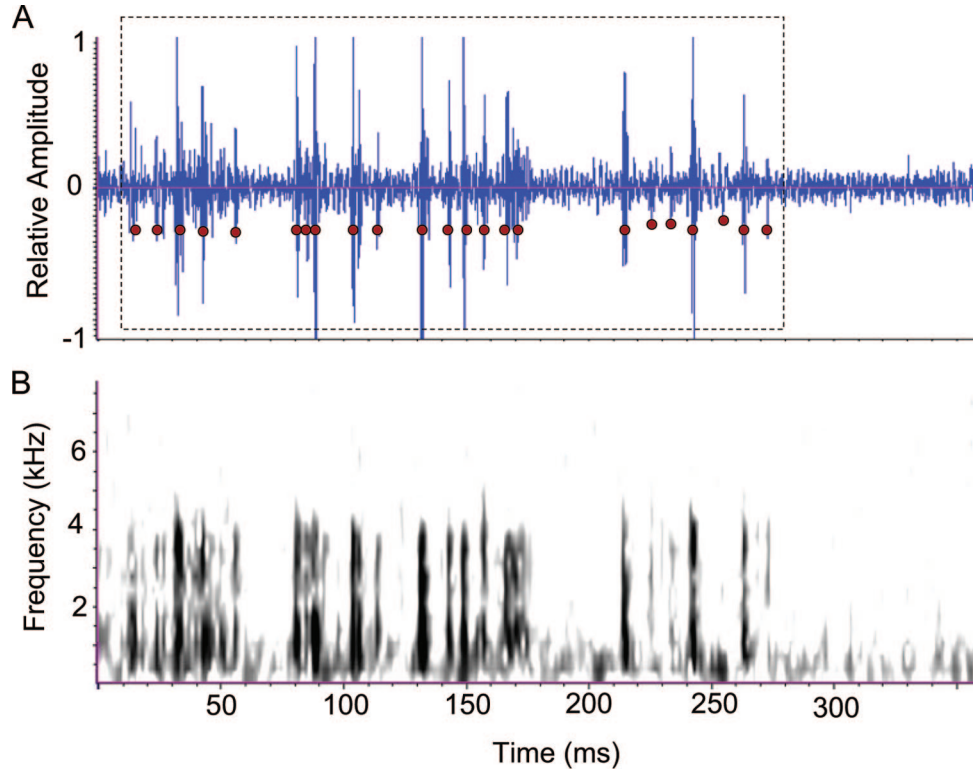

Fig. 2. Expanded version of second impulse train in Fig. 1, with solid dots in the oscillogram (A) marking the signals identified by computer as insect-produced impulses. Darker shades in the spectrogram (B) indicate frequencies with higher signal energies at the specified time. (Online figure in color.)

Spectral Profile Analyses for Targeting Sugarcane Pests. To identify distinctive characteristics of *D. albohirtum* larval scrapes and other behaviors, we first constructed spectral profiles (Mankin 1994; Mankin et al. 2000, 2008b) of impulses from distinctive scrapes recorded from sample sites where only these larvae had been recovered. One profile (*ACC-albo*) was constructed from a series of 45 impulse trains recorded by accelerometer during a period of low background noise. A second profile (*AED-albo*) was constructed from a series of 22 impulse trains recorded by the AED-2000, also during a period of low background noise.

The profiles were tested for their capability to distinguish insect sounds from background noise by first processing the recordings from all sample sites and then conducting a review in Raven of impulse trains that failed to match the profiles. The review indicated that listeners usually classified signals in recordings from the Mackay region as insect sounds when their impulses matched the *ACC-albo* profile, but in recordings from the Bundaberg region, many of the signals that listeners classified as insect sounds were rejected by the *ACC-albo* profile. Searching for a set of distinctive impulse trains produced by economically important *A. parvulus* larvae, we reprocessed accelerometer recordings from sites where only *A. parvulus* had been recovered near Bundaberg. Listeners identified a series of 22 impulse trains in Raven that were interpretable as a distinctive insect-produced series of sounds, and a spectral profile, *ACC-parv*, was constructed as an averaged spectrum of these trains in DAVIS (Mankin et al. 2000).

A search of the five recordings obtained where *L. crinita* larvae were recovered (Table 2) failed to identify a distinctive sound that might be used to construct a profile to distinguish *L. crinita* sounds from those produced by dynastines and rutelines. However, all five sample sites were identified at m_{edium} or h_{igh} likelihood of infestation (Table 2).

Spectral Analysis of Background Noises. The process of distinguishing larval sounds from background noise was sometimes complicated by the richly varied soundscape of the sugarcane field environment. An example in Fig. 3 shows an 18-s sample of background noise, parts of which were difficult to distinguish from insect sounds. The sample contains low- and high-pitched bird calls, the buzzing of a nearby fly, and numerous taps of leaves and stalks against each other during a light gust of wind. The bird-calls and fly-buzzing had energy in a narrow range of frequencies (Fig. 3B) and could be distinguished easily from the broad-band *D. albohirtum* signals (Figs. 1–2). However, the period of wind-induced leaf tapping in Fig. 3, like many similar periods of light wind recorded in this study, had significant broad-band energy. The

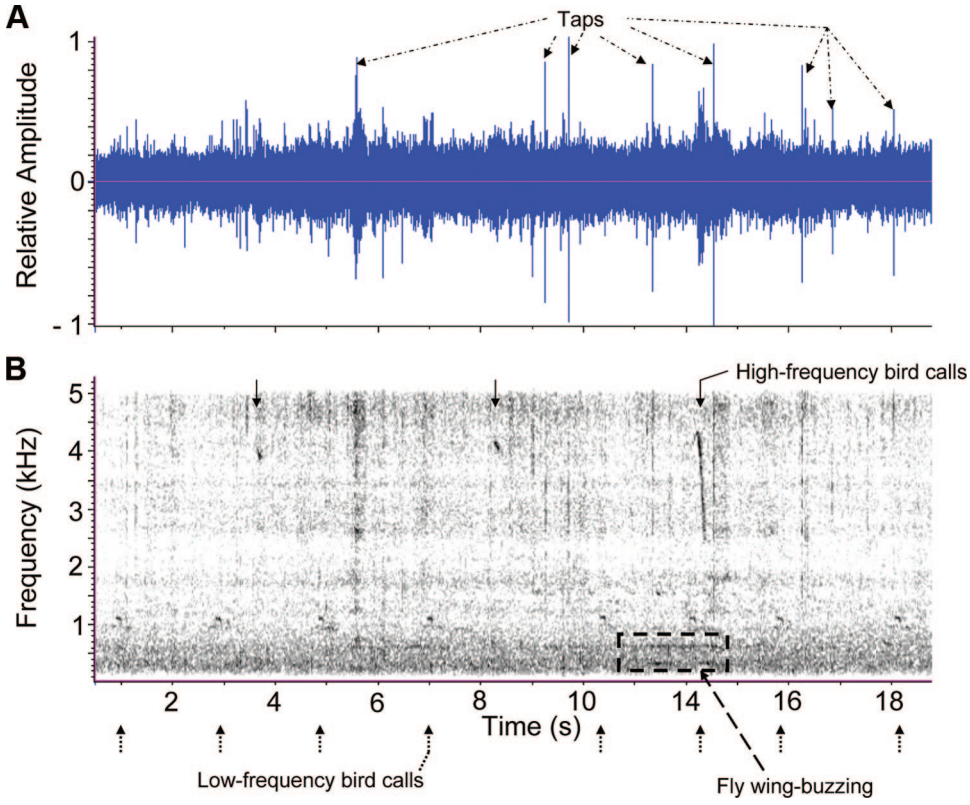

Fig. 3. Oscillogram (A) and spectrogram (B) of signals recorded by accelerometer in a sugarcane field near Mackay during a period of varied background noise. Dotted arrows indicate times of occurrence of low-frequency (1.1 kHz) bird calls. Solid arrows indicate higher frequency (2.7–4.0 kHz) bird calls. Dashed box indicates signals at 300- and 600-Hz harmonics of the wingbeat of a buzzing fly. Dot-dashed lines indicate taps caused by wind-induced movement of leaves or stalks against each other. Darker shades in the spectrogram indicate frequencies with higher signal energy at the specified time. (Online figure in color.)

mean leaf-tapping signal (*ACC-leaf taps*), constructed from the eight taps in Fig. 3, is compared with *ACC-albo* and *ACC-parv* larval spectral profiles in Fig. 4. A similar profile for leaf-tapping signals detected by the AED-2000, *AED-leaf taps*, was constructed from a series of ten taps in a recording obtained from the Bundaberg region.

The spectra of leaf-tapping signals are different from and less easily filtered than the low-frequency spectra of moderate to strong wind, e.g., the signals occurring at the beginning and end of the sample in Fig. 1, or other examples shown in Mankin et al. (2000) and Mankin and Benshemesh (2006). One potential method for discriminating the leaf-tapping signals from insect sounds was to consider differences in the temporal patterns of the leaf taps, other background noises, and insect sounds.

Temporal-Pattern Analysis. In replays of recordings from Mackay and Bundaberg, listeners regularly detected signals reminiscent of previous studies (Mankin et al. 2008a,b), where trains contained a different distribution of impulse counts when insects were present than when they were absent. To determine whether trains from either or both *D. albohirtum* and *A. parvulus* contained a relatively delimited range of impulse counts, we reexamined in Raven the recordings obtained from sample sites where only *D. albohirtum* or *A. parvulus* were recovered, and examined the distributions of the numbers of impulses in larval and background noise trains.

Listener assessments of accelerometer recording playbacks suggested that the minimum number of impulses in trains easily identifiable as *D. albohirtum* sounds was $n_{l\text{-}albo} = 3$, and the maximum was $n_{u\text{-}albo} = 50$ (see Materials and Methods). Signals outside these ranges were less likely to be assessed by listeners as insect-produced sounds (bursts) and were more likely to be assessed as wind or other background noises. Examination of distributions of *ACC-albo* impulse trains classified using the DAVIS signal processing program revealed a similar, delimited range of impulse numbers in pulse trains identified as *D. albohirtum* sounds. In recordings from sample sites in the Bundaberg region where only *A. parvulus* was recovered, the minimum number of *ACC-parv* impulses in trains easily identifiable as an *A. parvulus* sound (burst) was $n_{l\text{-}parv} = 5$ and the maximum was $n_{u\text{-}parv} = 50$. Impulse trains in AED-2000 recordings at sites near Mackay

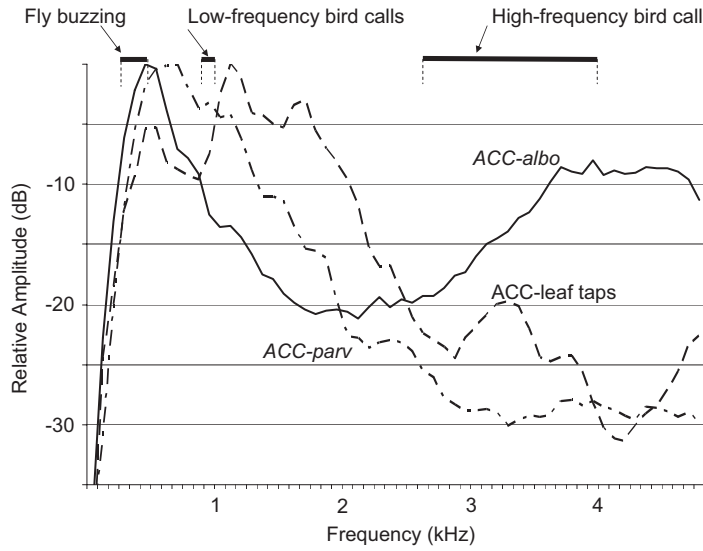

Fig. 4. Spectral profiles of impulses recorded at sample sites verified to contain one or more *D. albohirtum* larvae, *ACC-albo* (45 trains recorded near Mackay), and *A. parvulus* larvae, *ACC-parv* (22 trains recorded near Bundaberg), compared with a spectral profile of leaf taps produced during a gust of light wind at a different sample site near Mackay (15 impulse trains). Dashed vertical lines indicate the relatively narrow frequency ranges of fly buzzing and bird calls that could be easily distinguished from the broadband signals of white grub sounds. Spectrum level is relative to the maximum acceleration measured in the 0.2–5 kHz reference range.

where only *D. albohirtum* were recovered and at sites near Bundaberg where only *A. parvulus* were recovered had distributions similar to those found in the accelerometer recordings at those sites.

The cut-off counts for *D. albohirtum* and *A. parvulus* bursts overlapped in both the accelerometer and the AED-2000 recordings. Consequently, the temporal pattern analysis was useful primarily as a means to distinguish insect sounds from background noise in this study, rather than as a means to distinguish different species from each other.

Rates of Trains and Bursts Associated with *D. albohirtum* and *A. parvulus* at Sample Sites. Using the spectral profiles and burst cut-off counts described above for signals produced by *D. albohirtum* and *A. parvulus* larvae, we processed the complete set of accelerometer and AED-2000 recordings using the DAVIS signal processing program. The rates of trains and bursts detected by accelerometer with impulses that matched the *ACC-albo* profile, $r_{ACC\text{-}albo\text{-}t}$ and $r_{ACC\text{-}albo\text{-}b}$, respectively, are listed in Table 1 in order of the numbers of *D. albohirtum* recovered at each sample site near Mackay. Table 2 lists the rates of trains and bursts that matched the *ACC-parv* profile at sample sites near Bundaberg, $r_{ACC\text{-}parv\text{-}t}$ and $r_{ACC\text{-}parv\text{-}b}$, in relation to the numbers of *Antitrogus* spp., *L. crinita*, Rutelinae, and other organisms. In the signals recorded near Bundaberg, it was not possible to distinguish between *A. parvulus* and *A. consanguineus*. Both species are considered to be sugarcane pests (Allsopp et al. 1994, McGill et al. 2003), so their counts were combined in the analyses. Table 3 lists the rates of valid trains and bursts, $r_{AED\text{-}albo\text{-}t}$ and $r_{AED\text{-}albo\text{-}b}$, respectively, detected at all sample sites where the AED-2000 system was used. The rates are shown in relation to the counts of *Antitrogus* spp., *D. albohirtum*, Rutelinae, and other organisms recovered.

Rank-order correlation coefficients were calculated for relationships between the numbers of organisms of different types recovered at different sample sites and the rates of valid trains and bursts detected (Table 4). Counts of Rutelinae were not correlated with rates of *ACC-albo*, *ACC-parv*, or *AED-albo* trains or bursts. Counts of *D. albohirtum* were significantly correlated with $r_{ACC\text{-}albo\text{-}b}$, and *Antitrogus* spp. counts were significantly correlated with $r_{ACC\text{-}parv\text{-}t}$ and $r_{ACC\text{-}parv\text{-}b}$. Otherwise, the only significant correlation was between counts of *Dasygnathus*, etc., and $r_{ACC\text{-}albo\text{-}t}$ (but not $r_{ACC\text{-}albo\text{-}b}$) at sample sites near Mackay. In this case, the correlation was negative. A possible cause of a negative correlation could be that *Dasygnathus* larvae produce trains with impulses having their own distinctive spectral patterns, different from the *ACC-albo* profile, which might mask impulse trains that otherwise would have matched the *ACC-albo* profile. We did not construct a profile of *Dasygnathus* impulse trains for this report, but distinctive stridulatory chirps, described in Mankin et al. (2009), were detected at two sample sites where *Dasygnathus* were recovered.

Given the weakness of any direct relationship between the counts of targeted insects, *D. albohirtum* and *Antitrogus* spp., and the rates of *ACC-albo*, *ACC-parv* or *AED-albo* trains or bursts, we considered the possibility of a categorical relationship by constructing indicators of infestation likelihood at sample sites (Mankin et al. 2007, 2008b; see Materials and Methods). The results in Tables 1–3 suggested cut-off rates such as

Table 3. Numbers of organisms, listener assessments of infestation likelihood, and rates of trains and bursts of impulses that matched the *AED-albo* spectral profile at sample sites near Mackay or Bundaberg, arranged in order of rates of valid bursts, $r_{AED\text{-}albo\text{-}b}$

Region	No. organisms recovered				Assessed likelihood	Rate (no./min) of	
	Antitr.[a]	Dalb.[b]	Rtl.[c]	Other[d]		Trains[e]	Bursts[f]
Bundaberg	5	0	0	1	m_{edium}	51.75	19.86
Bundaberg	4	0	0	0	h_{igh}	71.62	19.70
Mackay	0	2	0	0	h_{igh}	64.75	18.62
Bundaberg	2	0	0	1	h_{igh}	76.37	17.76
Bundaberg	6	0	0	0	h_{igh}	59.65	15.97
Mackay	0	1	1	8	h_{igh}	79.45	14.14
Mackay	0	3	1	0	m_{edium}	82.53	12.08
Bundaberg	0	0	0	1	m_{edium}	71.78	11.94
Bundaberg	1	0	5	1	h_{igh}	71.45	7.16
Bundaberg	0	0	0	5	m_{edium}	84.71	4.63
Bundaberg	0	0	0	2	m_{edium}	70.80	3.65

[a] *A. parvulus.*
[b] *D. albohirtum.*
[c] Rutelinae spp.
[d] Including dynastines, mole crickets, tenebrionids, wireworms, cockroaches, earthworms, centipedes, ants, chinch bugs, and cane toads.
[e] $rAED_{\text{-}albo\text{-}t}$ = no./min of trains containing a plurality of impulses that matched the *AED-albo* profile (constructed as a mean spectrum of 22 impulse trains, see *Methods*), where trains are groups of impulses distinguishable as distinct sounds (interpulse intervals <250 ms) (see Materials and Methods under Temporal Pattern Analyses).
[f] $r_{AED\text{-}albo\text{-}b}$ = no./min of *AED-albo* trains with $2 > n_t < 51$ impulses per train in recordings near Mackay, and $4 < n_t < 51$ impulses per train in recordings near Bundaberg (see Materials and Methods under Temporal Pattern Analyses).

those in listed Table 5, $r_{lower\text{-}t}$ and $r_{upper\text{-}t}$, for the trains indicators, $i_{ACC\text{-}albo\text{-}t}$, $i_{ACC\text{-}parv\text{-}t}$, and $i_{AED\text{-}albo\text{-}t}$, associated with impulse-train rates, $r_{ACC\text{-}albo\text{-}t}$, $r_{ACC\text{-}parv\text{-}t}$, and $r_{AED\text{-}albo\text{-}t}$, respectively. Table 5 also lists the estimated cut-off rates, $r_{lower\text{-}b}$ and $r_{upper\text{-}b}$ for the burst indicators, $i_{ACC\text{-}albo\text{-}t}$, $i_{ACC\text{-}parv\text{-}b}$, and $i_{AED\text{-}albo\text{-}t}$, associated with burst rates, $r_{ACC\text{-}albo\text{-}b}$, $r_{ACC\text{-}parv\text{-}b}$, and $r_{AED\text{-}albo\text{-}b}$, respectively. Based on these cut-offs, the distributions of computer-rated infestation likelihood among sample sites near Mackay where *D. albohirtum* were present or absent, and among sample sites near Bundaberg where *Antitrogus* spp. were present or absent are shown in Table 6 for ratings based on trains indicators, and in Table 7 for ratings based on bursts indicators.

The bursts indicator was more reliable than the trains indicator in distinguishing the absence or presence of *D. albohirtum* and *Antitrogus* spp. The distribution of ratings of h_{igh}, m_{edium}, or l_{ow} infestation likelihood was significantly different for sample sites where *D. albohirtum* was absent or present near Mackay, and for *Antitrogus* spp. near Bundaberg (Table 7). With the trains indicator, however, the distribution of accelerometer-based ratings at sample sites near Bundaberg was different between sites with *Antitrogus* spp. absent or present, but the distribution at sites near Mackay was not different between sample sites with *D. albohirtum* absent or present. The distribution of AED-2000 trains indicator ratings was not significantly different between sample sites that did or did not contain the target pest (Table 6).

Without further study, it is not certain whether there is a practical difference in the field between the

Table 4. Spearman's rank correlation coefficients, r_s, for relationships between number of organisms recovered and rates of trains and bursts detected by: accelerometer (ACC) near Mackay, $r_{ACC\text{-}albo\text{-}t}$, and $r_{ACC\text{-}albo\text{-}b}$, respectively; by ACC near Bundaberg, $r_{ACC\text{-}parv\text{-}t}$ and $r_{ACC\text{-}parv\text{-}b}$, respectively; or by AED-2000 (AED), $r_{AED\text{-}albo\text{-}t}$, and $r_{AED\text{-}albo\text{-}b}$, respectively, at sample sites near Mackay or Bundaberg

Instrument/region (no. sites)	Category of organisms recovered	Trains (no./min)		Bursts (no./min)	
		r_s	P	r_s	P
ACC/Mackay (27)	*D. albohirtum*	0.3132	0.1114	0.4228	0.028
	Dasygnathus, etc.[a]	−0.4110	0.0332	−0.3716	0.0563
	L. frenchi	−0.126	0.5311	−0.2424	0.2232
	Rutelinae	0.0245	0.9034	−0.0210	0.9171
ACC/Bundaberg (18)	*Antitrogus* spp.	0.5471	0.0188	0.4710	0.0485
	Dynastines, etc.[b]	0.2976	0.2304	0.2239	0.3717
	Rutelinae	0.0983	0.6981	0.0625	0.8054
	L. crinita	-0.03	0.9058	−0.0118	0.9630
AED/All[c] (11)	*Antitrogus* spp.	−0.5651	0.0701	0.05998	0.0511
	Dynastines, etc.[d]	0.3623	0.2735	−0.5196	0.1014
	Rutelinae	0.3307	0.3205	−0.2843	0.3968
	D. albohirtum	0.2659	0.4293	0.1156	0.735

[a] See footnote *d,* Table 1.
[b] See footnote *d,* Table 2.
[c] Includes three AED recordings near Mackay and eight near Bundaberg. As in Table 3, only impulses that matched the *AED-albo* spectral profile were included in AED trains. In recordings near Mackay, bursts were AED trains with $2 > n_t < 51$ impulses per train, and in recordings near Bundaberg, bursts were AED trains with $4 > n_t < 51$ impulses per train.
[d] See footnote *d,* Table 3.

Table 5. Estimated lower and upper cutoff rates for infestation likelihood indicators based on rates of detection by accelerometer (ACC) or AED-2000 (AED) of trains and bursts of impulses matching the spectral profiles for *D. albohirtum* signals at recording sites near Mackay (*ACC-albo* or *AED-albo*) and spectral profiles for *A. parvulus* signals near Bundaberg (*ACC-parv* or *AED-albo*)

Spectral profile	Infestation likelihood indicator cut-off rate			
	Impulse trains (trains/min)		Impulse bursts (bursts/min)	
	$r_{lower\text{-}t}$	$r_{upper\text{-}t}$	$r_{lower\text{-}b}$	$r_{upper\text{-}b}$
ACC-albo	1.0	2.0	0.25	0.75
ACC-parv	5.0	21.0	1.4	5.0
AED-albo	55.0	75.0	5.0	12.0

use of burst indicator ratings ($P = 0.01–0.03$; Table 7) or trains indicator ratings ($P = 0.02–0.06$) in signals recorded by accelerometer. From a statistical perspective, however, we can conclude that infestation likelihood indicators based on the rates of bursts detected at recording sites provide a more reliable prediction of absence or presence of white grubs than the use of sound rates alone (Table 4; Mankin et al. 2007) or the use of indicators based on the rates of impulse trains detected (Table 6) in recordings made with either the accelerometer or AED-2000.

Rapid Survey. The results from testing an AED-2000 system in a rapid survey of sugarcane in a field near Bundaberg (see Materials and Methods) are listed in Table 8. Each of three listeners monitored sounds recorded at 13 sample sites for 2-min periods, and at least one listener assessed each site at m_{edium} or h_{igh} likelihood of insect presence. Sound-producing insects were recovered at each sample site. In general, the listener and computer ratings were in close agreement, as has been seen in previous acoustic detection studies (Mankin et al. 2007). However, five (39%) of the sample sites where *A. parvulus* was recovered (the last five sites in Table 8) would have been rated at l_{ow} likelihood of infestation using the *AED-albo* bursts or trains criteria in Table 5. In cases where speed of assessment is not a critical factor, sampling for the longer, 3-min periods used at the other sample sites in this study may increase detection of larvae that are active during only a small part of the sampling period.

The three-listener panel completed the survey in 130 min, an average of 10 min per sample site, or 3.3 min per listener per site. This is approximately the same as the time required per listener per site when using an accelerometer system to conduct a 2-min assessment of infestation. In both cases, a heavily infested sample site would require less time than a lightly infested one because large numbers of impulses

Table 6. Distributions of computer-rated infestation likelihood among sample sites where targeted larvae (*D. albohirtum* or *Antitrogus* spp.) were absent or present, with indicator variables estimated from observed distributions of the rates of trains, $r_{ACC\text{-}albo\text{-}t}$, $r_{ACC\text{-}parv\text{-}t}$, or $r_{AED\text{-}albo\text{-}t}$, with impulses matching the spectral profiles, *ACC-albo*, *ACC-parv*, or *AED-albo*, respectively

Likelihood indicator rating	No. sites rated at listed likelihood with targeted larvae absent or present					
	ACC-albo profile[a]		*ACC-parv* profile[b]		*AED-albo* profile[c]	
	Absent	Present	Absent	Present	Absent	Present
l_{ow}	3	7	3	1	0	1
m_{edium}	0	4	3	5	2	4
h_{igh}	0	13	0	6	1	3

[a] $P = 0.056$ that trains indicator, $i_{ACC\text{-}albo\text{-}t}$, is independent of absence or presence of *D. albohirtum* at sample sites near Mackay (Wilcoxon two-sample exact test: S = 18.0, Z = −2.00).

[b] $P = 0.016$ that trains indicator, $i_{ACC\text{-}parv\text{-}t}$, is independent of absence or presence of *Antitrogus* spp. at sample sites near Bundaberg (Wilcoxon two-sample exact test: S = 33.0, Z = −2.36).

[c] $P = 0.64$ that trains indicator, $i_{AED\text{-}albo\text{-}t}$, is independent of absence or presence of *D. albohirtum* at sample sites near Mackay and of *Antitrogus* spp. at sample sites near Bundaberg (Wilcoxon two-sample exact test: S = 18.5, Z = 0.0).

Table 7. Distributions of computer-rated infestation likelihood among sample sites where targeted larvae (*D. albohirtum* or *Antitrogus* spp.) were absent or present, with indicator variables estimated from observed distributions of the rates of bursts, $r_{ACC\text{-}albo\text{-}b}$, $r_{ACC\text{-}parv\text{-}b}$, or $r_{AED\text{-}albo\text{-}b}$, with impulses matching the spectral profiles, ACC-albo, ACC-parv, or AED-albo, respectively

Likelihood indicator rating	No. sites rated at listed likelihood with targeted larvae absent or present					
	ACC-albo profile[a]		*ACC-parv* profile[b]		*AED-albo* profile[c]	
	Absent	Present	Absent	Present	Absent	Present
l_{ow}	3	5	5	2	2	0
m_{edium}	0	5	1	6	1	1
h_{igh}	0	14	0	4	0	7

[a] $P = 0.029$ that bursts indicator, $i_{ACC\text{-}albo\text{-}b}$, is independent of absence or presence of *D. albohirtum* at sample sites near Mackay (Wilcoxon two-sample exact test, S = 15.0, Z = −2.20).

[b] $P = 0.009$ that bursts indicator, $i_{ACC\text{-}parv\text{-}b}$, is independent of absence or presence of *Antitrogus* spp. at sample sites near Bundaberg (Wilcoxon two-sample exact test: S = 31.0, Z = −2.55).

[c] $P = 0.012$ that bursts indicator, $i_{AED\text{-}albo\text{-}b}$, is independent of absence or presence of *D. albohirtum* at sample sites near Mackay and of *Antitrogus* spp. at sample sites near Bundaberg (Wilcoxon two-sample exact test: S = 6.5, Z = −2.66).

Table 8. Numbers of organisms recovered at rapid-survey sample sites near Bundaberg, assessments of the likelihood of infestation by a 3-listener panel, and the rates of AED-albo trains and bursts, $r_{AED\text{-}albo\text{-}t}$ and $r_{AED\text{-}albo\text{-}b}$, respectively, arranged in order of rates of bursts, $r_{AED\text{-}albo\text{-}b}$

No. *A. parv*, *L. neg*[a]	No. other organisms[b]	Assessments of infestation likelihood				
		Listener panel			Trains/min	Bursts/min
5	0	h_{igh}	h_{igh}	h_{igh}	49.4	34.0
8	0	m_{edium}	l_{ow}	l_{ow}	57.2	25.6
0	5	m_{edium}	m_{edium}	m_{edium}	72.6	14.5
24	1	h_{igh}	h_{igh}	m_{edium}	55.8	13.7
1	0	h_{igh}	l_{ow}	l_{ow}	80.0	13.6
8	0	h_{igh}	m_{edium}	m_{edium}	76.5	12.4
11	0	m_{edium}	m_{edium}	m_{edium}	79.8	10.1
13	0	m_{edium}	l_{ow}	m_{edium}	65.1	6.6
7	0	m_{edium}	l_{ow}	l_{ow}	32.7	3.6
6	0	h_{igh}	m_{edium}	l_{ow}	75.4	2.8
8	0	m_{edium}	l_{ow}	m_{edium}	23.0	0
6	0	m_{edium}	m_{edium}	l_{ow}	37.5	0
6	0	m_{edium}	l_{ow}	l_{ow}	33.8	0

[a] *A. parvulus* and *L. negatoria.*

[b] Included Dynastinae and Rutelinae.

would be detected immediately after recording began. In comparison, excavating samples to assess infestation requires 10–12 min per sample site on average (K.J.C., unpublished), longer than the 3.3 min required for an acoustic assessment. Sorting through a lightly infested sample might take even longer if the surveyor searches more intently to be sure that no larvae have been missed.

Discussion

A salient finding of this study was that *D. albohirtum* larvae had notably distinctive patterns of activity in recordings at sample sites near Mackay, producing bursts of impulses that were easily identified as insect sounds by listeners and by computer software (Table 7). Similarly, *Antitrogus* spp. larvae produced distinctive impulse trains (Table 6) and bursts (Table 7) in recordings at sample sites near Bundaberg. With ≈1-h practice, a grower or advisor could become proficient at recognizing such patterns and then could use an acoustic sensor as a survey tool for detection of *D. albohirtum* or *Antitrogus* spp. infestations.

Such results suggest considerable potential benefits from incorporating acoustic methods in efforts to manage Australian sugarcane pests. GrubPlan (Hunt et al. 2002) and other pest risk assessment and management programs have been developed to reduce economic losses to sugarcane growers in Australia, but their widespread adoption has been hampered by the labor and time involved in excavating cane stools to assess insect populations. Successful adoption of acoustic technology could help reduce the necessary labor and time. It is physically difficult for a surveyor to excavate and assess >30 samples per day unless the soil and environmental conditions are highly favorable. Sandy soil is less difficult to dig up than hard clay, but small white grubs in sandy soil are more difficult to see and take longer to assess than Childers grubs in red hard soil. ≈10–12 min is required to excavate and sort a sample, whereas only 3–5 min is required for an individual surveyor to insert a waveguide into the soil and acoustically assess the likelihood of infestation (see Rapid Survey). With both acoustic and soil sampling, large infestations can be detected more quickly and easily than small infestations, so the two methods have similar tradeoffs between the accuracy of detection and the time spent in listening to or sorting through a lightly infested or heavily infested sample.

There are benefits to using both excavation and acoustic methods together in a sampling program. Under a sequential sampling plan developed for monitoring of sugarcane (Allsopp and Bull 1989), a surveyor might begin with acoustic sampling and excavate a stool to confirm which species is present when an acoustic signal is detected. In high populations, the sampling could terminate after signals were detected at five stools and confirmed by excavation. At intermediate population densities (especially in very large fields) sampling might have to continue beyond five, up to 20 or more, to determine population density with a precision of at least 0.25. With low populations, sampling could be terminated after five negative samples. A benefit of incorporating acoustic technology into the survey process would be that if no larval scraping or other distinctive behaviors were detected at a recording site, a surveyor could move quickly to another site and save the labor of digging up a sample that likely contained no targeted white grubs. Excavations could be reserved to those recording sites where signals were detected and one or more targeted white grubs were likely to be present.

We note that if acoustic surveys are to be incorporated into the sequential sampling plans without always an accompanying excavation at each sample, it will be necessary to first recalibrate the stop lines in terms of acoustic parameters. Acoustic surveys do not directly measure the cumulative counts of insects that typically are used in determining when sampling can be terminated (Allsopp and Bull 1989, Pedigo and Buntin 1994). A different scale could be developed, e.g., the infestation likelihood indicators could be scaled quantitatively as $l_{ow} = 0$, $m_{edium} = 1$, and $h_{igh} = 2$, in which case it would be possible to recalibrate the stop-sampling lines on the basis of the new scale. Examples of other scales that have been used in sequential sampling include visual assessment (Meikle et al. 2000) and cumulative numbers of infested subsamples (Fidgen et al. 2006).

Incremental improvements to currently available acoustic detection systems could encourage adoption of programs such as GrubPlan. Multiple sampling points might be set up semipermanently with wireless transmission of signals or alerts (Butler et al. 2006) to reduce the labor involved in inserting nails and attaching acoustic sensors. The acoustic instruments could be made more portable and robust to accommodate the high temperatures and humidities and the high densities of plants in sugarcane field environments. Additional experience with recordings from dynastine larvae may lead to improved capability to identify dynastine larvae separately from *D. albohirtum.* Further experience with recordings from *L. crinita* larvae may lead to development of a profile that distinguishes them from dynastines, rutelines, and other nontarget insects in the small region around Bundaberg where its populations achieve pest status.

Perhaps most importantly, opportunities remain for reductions in the cost of the instruments and improvements in the computer software. Although they provided assistance in identifying *D. albohirtum* and *Antitrogus* spp. when these larvae were present, with or without nontarget species (Table 7), the acoustic indicators constructed in this report did not directly discriminate between the targeted insects and nontarget insects. If *D. albohirtum* and *Antitrogus* spp. were present in the same fields, it might be possible to distinguish their signals in accelerometer recordings based on differences between the *ACC-albo* and *ACC-parv* profile. However, these two species have different regional distributions and are not usually found together. The procedures for identification of specific signals produced by targeted insects possibly could be improved by incorporation of recently developed

speech recognition techniques, including Gaussian mixture modeling (Pinhas et al. 2008) and hidden Markov models (Trifa et al. 2008), as well as with new statistical methods for identifying insect signals in noise (de la Rosa et al. 2008). Such improvements also would expand the applicability of acoustic detection systems for monitoring of insects in container crops (Mankin and Fisher 2002) or detection of exotic pests in trees (Mankin et al. 2008a,b).

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