Acoustic Indicators for Mapping Infestation Probabilities of Soil Invertebrates

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J. Econ. Entomol. 100(3): 790–800 (2007)

ABSTRACT Acoustic and traditional excavation methods were used in consecutive summers to conduct two geospatial surveys of distributions of white grubs and other soil invertebrates in two forage fields. Indicator variables were constructed from listener- and computer-based assessments of sounds detected at each recording site and then applied in geostatistical analysis, contingency analysis, and spatial analysis of distance indices (SADIE) of soil invertebrate distributions. Significant relationships were identified between the acoustic indicators and the counts of sound-producing soil invertebrates in a majority of the geostatistical and contingency analyses. Significant clusterings and overall spatial associations were identified also in most of the SADIE analyses. In addition, significant local spatial associations were identified between acoustic indicators and counts of sound-producing soil invertebrates that could be of potential value in selection of specific sites as targets for treatment or for untreated reserves in integrated pest management programs. An example is presented of the relative efficiency of acoustic surveys for targeting of white grub treatments.

KEY WORDS sound, geospatial mapping, SADIE, geostatistics, soil insects

Soil-dwelling insects have important effects on agricultural yields, but their concealment makes them difficult to manage (Vittum et al. 1999). They remain a poorly understood component of the ecosystem (Blossey and Hunt-Joshi 2003, Poveda et al. 2006), and little is known about their distribution, abundance, and behavior (Hunter 2001). Greater understanding of the distributions of soil-insect pests is needed for development of improved management strategies (Villani et al. 2002).

Surveys were conducted in 1997 and 1998 in forage fields at Auburn and Grove Hill, AL, to obtain information about distributions of white grubs and other soil invertebrates and to compare traditional excavation with newly developed acoustic methods that had potential to facilitate monitoring activities (Brandhorst-Hubbard et al. 2001). The Auburn 1998 survey was not analyzed, due to high levels of noise that interfered with the procedures then used to discriminate valid sounds from background. In the three analyzed surveys, estimates of distributions determined by excavation were compared with estimates by methods that had been adapted from acoustic studies of hidden stored-product insect infestations (Mankin et al. 2000). A positive correlation was found between kriged (spatially interpolated) estimates of log-transformed rates of soil invertebrate sound pulses and kriged estimates of log-transformed counts of sound-producing soil invertebrates in the Auburn 1997 survey. However, the correlations were not significant for surveys conducted either year at Grove Hill.

Evaluation of the methods and results of the initial study led to more powerful signal processing procedures and consideration of alternate analyses for relating acoustic measurements to observed soil invertebrate distributions. Other field studies have found that the presence/absence of characteristic sound pulses is a good indicator of insect presence/absence, but the relationship between sound-rate and soil invertebrate numbers is relatively weak (Mankin et al. 2001, Mankin and Lapointe 2003, Zhang et al. 2003). Thus, an indicator variable (Goovaerts 1998, Clark and Harper 2000) that categorizes the likelihood of infestation may be better correlated with the observed infestation than the log-transformed sound-rate variable originally tested by Brandhorst-Hubbard et al. (2001). Indicator variables are of particular utility in contingency analyses and in a spatial mapping application that was developed after the initial report was published, spatial analysis of distance indices (SADIE) (Perry and Dixon 2002), which estimates spatial patterns of individual data sets and maps local spatial associations between pairs of data sets. Mapped estimates of infestation likelihood have potential application in site-specific integrated pest mangement programs that target insect pests (Fleischer et al. 1999) or

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that target low-risk areas for reduced pesticide use to avoid pesticide resistance or to conserve natural enemies (Midgarden et al. 1997). For this report on the complete series of forage field surveys, we tested improved tools for discriminating soil invertebrate sounds from background noise, and we examined the use of discretized (categorized) acoustic indicators as variables for geostatistical analysis, contingency analysis, and SADIE analysis of relationships between traditional and acoustic surveys.

Materials and Methods

Survey Sites, Soil Invertebrate Environment, and Acoustic Environment. The surveys were conducted in two mixed Bermuda grass, *Cynodon dactylon* (L.) Pers., and bahiagrass, *Paspalum notatum* Flüggé, hayfields in sandy loam soil at Auburn (Lee Co.) and Grove Hill (Clarke Co.) during late August to mid-September, a period when white grubs were expected to be active and feeding. No precipitation occurred at either site during the survey periods, and the daily maximum and minimum soil temperatures at 10-cm depth were similar across the surveys (http://lwf.ncdc.noaa.gov), with a maximum of 37.8°C both years at Auburn. The minimum soil temperature during the Auburn surveys was 26.1°C in 1997 and 24.4°C in 1998. The maximum at Grove Hill was 36.1°C in 1997 and 37.8°C in 1998. The minimum at Grove Hill was 28.3°C in 1997 and 27.8°C in 1998. Wind speeds were not measured, but the observation notes indicated that windy conditions contributed to high levels of background noise in the Grove Hill 1997 survey. In general, there was greater vehicular noise both years at the Grove Hill site, but in 1998, background noise from a marching band practice interfered with some of the recordings at Auburn. Varying levels of interference from vehicular and human activities and wind was probably the greatest contributor to variation in the capability to detect soil invertebrates in the different surveys.

Sampling and Acoustic Signal Processing Procedures. Details of the excavation and acoustic sampling procedures for the Auburn 1997, Grove Hill 1997, and Grove Hill 1998 surveys (Brandhorst-Hubbard et al. 2001) were similar to those described here for Auburn 1998. Positions of 169 sample sites, spaced 7 m apart by using Vision System (Rockwell Collins, Cedar Rapids, IA) global positioning system (GPS) software, were logged by a model 7000 Differential GPS System (OmniSTAR, Inc., Houston, TX). A 15-cm-long soil microphone probe (Sonometrics, Huntington Woods, MI) was inserted into the ground at each sampling site, and 180-s recordings were collected on a digital audio tape recorder (model DA-P1, TASCAM, Montebello, CA). After recording, two 10-cm-diameter by 15-cm-depth soil cores were excavated at the left and right of the probe. Visible invertebrates were extracted from the soil, counted, and stored in 70% ethanol in labeled vials.

The recorded signals were processed by software described in Mankin et al. (2000) and Mankin et al. (2001) to exclude sounds that were not produced by soil invertebrates. The processing involved comparisons between the spectrum of each individual sound pulse and a set of spectral profiles constructed as averages of validated invertebrate sound or background noise spectra (see Auburn 1998 Spectral Profiles in Results).

Geostatistical Modeling of Invertebrate and Sound-Rate Distributions. Nested indicator kriging (e.g., Goovaerts 1998, Clark and Harper 2000) was performed on indicator variables derived from $sr(\mathbf{p})$, the rate of valid sound pulses, and $n(\mathbf{p})$, the number of sound-producing invertebrates, at position, $\mathbf{p}(x, y)$, in the forage field. The indicator for sound-rate was calculated using a discretization procedure with two threshold cutoffs, sr_{lower} and sr_{upper}:

$$i_{\mathrm{sr}}(\mathbf{p}, k) = \left\{\begin{matrix} 1 & \text{if } sr(\mathbf{p}) \geq \mathrm{sr}_k & \\ & & k = lower,\ upper \\ 0 & \text{otherwise,} & \end{matrix}\right\} \qquad [1]$$

where $i_{\mathrm{sr}}(\mathbf{p}, k)$, is the k component of the indicator variable for $sr(\mathbf{p})$. Based on previous findings of background noise sound-rates ranging primarily from 10 to 21 pulses $\cdot$ min^{-1} in the Auburn 1997 survey (Brandhorst-Hubbard et al. 2001), we set the threshold cutoffs conservatively at $\mathrm{sr}_{lower} = 10.01$ pulses $\cdot$ min^{-1} and $\mathrm{sr}_{upper} = 21.99$ pulses $\cdot$ min^{-1}.

The indicator for $n(\mathbf{p})$, the number of sound-producing invertebrates, was discretized as

$$i_{\mathrm{n}}(\mathbf{p}, k) = \left\{\begin{matrix} 1 & \text{if } n(\mathbf{p}) \geq \mathrm{n}_k & \\ & & k = lower,\ upper \\ 0 & \text{otherwise,} & \end{matrix}\right\} \qquad [2]$$

where $i_{\mathrm{n}}(\mathbf{p}, k)$ is the k component of the indicator variable for $n(\mathbf{p})$, and n_k is the kth threshold for n. Thresholds of 0.5 and 1.5 were set in equation 2 for n_{lower} and n_{upper}, respectively, to distinguish between $n = 0$, $n = 1$, and $n > 1$.

Geostatistical modeling and kriging calculations were conducted using Geostokos Toolkit (Clark 2004). The kriging procedure yielded probability estimates for each of the indicator variable components, but for plotting and analysis, it was preferable first to convert the probability estimates for i_{n} back into quantitative estimates of the numbers of sound-producing soil invertebrates, $n(\mathbf{p})$, by using grid math in Surfer (Golden Software Inc. 1999). Then, the relationship between the $i_{\mathrm{sr}}(\mathbf{p}, upper)$ kriged estimates and $n(\mathbf{p})$ was evaluated by correlation analysis in a spreadsheet (Excel, Microsoft, Redmond, WA).

Contingency and SADIE Analyses of Acoustic Indicator Probabilities. Two methods were used to develop acoustic indicator variables for contingency analyses and SADIE (http://www.rothamsted.bbsrc.ac.uk/pie/sadie/SADIE_home_page_1.htm). One method involved playback of recordings by listeners who had previous laboratory and field experience in identifying soil invertebrate sounds and discriminating them from background noise (Everett Foreman, Betty Weaver in

Acknowledgments, and R.W.M.). In assessing the recordings, listeners also evaluated any explanatory notes written at the sampled sites, with particular attention to comments about wind or other background noise that might interfere with acoustic signal interpretation.

The listener assessment procedure was similar to that described in Mankin et al. (2001) for onsite rating of the likelihood of infestation (see Best et al. 2005 for additional discussion of listener identification of target sounds). The rating at each sampled position, **p**, was $la(\mathbf{p}) = \{$*low,* with no valid pulses or only a few faint pulses during a 180-s recording period; *medium,* with sporadic or faint groupings of valid pulses; or *high*, with easily detectable, frequent groups of valid pulses$\}$. For quantitative analyses, a listener assessment indicator variable was set as

$$i_{la}(\mathbf{p}) = \begin{Bmatrix} 2 & \text{if } la(\mathbf{p}) = high \\ 1 & \text{if } la(\mathbf{p}) = medium \\ 0 & \text{if } la(\mathbf{p}) = low. \end{Bmatrix} \quad [3]$$

The listener assessment at each site was complemented by a computer-based, sound-rate assessment of infestation likelihood, similar to the rating in Mankin et al. (2001). A recording site was assessed to have $sra(\mathbf{p}) = \{$*low, medium,* or *high*$\}$ likelihood of infestation by comparing its sound-rate to *low* and *high* threshold cutoffs. For quantitative analyses, a sound-rate indicator variable was set as

$$i_{sra}(\mathbf{p}) = \begin{Bmatrix} 2 & \text{if } sra(\mathbf{p}) \geq \text{sra}_{high} \\ 1 & \text{if } sra(\mathbf{p}) \geq \text{sra}_{low} \\ 0 & \text{otherwise.} \end{Bmatrix} \quad [4]$$

The magnitudes of the sra_{high} and sra_{low} thresholds were estimated from the distributions of sound pulse rates at infested and uninfested sites by procedures described in Results under Contingency Analyses. The overall significance of correspondence between both $i_{la}(\mathbf{p})$ and $i_{sra}(\mathbf{p})$ indicator variables and the presence of absence of infestation at each recording site was tested by chi-square analysis as well as the significance of the relationship between $i_{la}(\mathbf{p})$ and $i_{sra}(\mathbf{p})$ across sites, by methods similar to those described in Mankin et al. (2001).

The SADIE method was applied to estimate $\chi_{n,sra}$, the local spatial association between the soil-invertebrate count at each recording site and the sound-rate indicator of infestation likelihood, $i_{sra}(\mathbf{p})$, and to estimate $\chi_{n,la}$, the local spatial association between the soil invertebrate count and the listener indicator of infestation likelihood, $i_{la}(\mathbf{p})$. The procedure involved calculation of cluster indices $z_k(\mathbf{p})$ at each sampling location, **p**, where $k = n$ for soil invertebrate counts, $k = sra$ for sound-rate assessments, and $k = la$ for listener assessments, and then calculating the product (Perry and Dixon 2002):

$$\chi_{n,ka} = (z_n(\mathbf{p}))(Z_{ka}(\mathbf{p})), \quad [5]$$

where $k_a = sra, la$.

The cluster index is calculated from the scaled distance to regularity, or minimum total distance that items in an observed arrangement are moved to obtain a mean number of items, *m,* at each of the *n* sample units in the arrangement (Perry and Dixon 2002). A group of sample units, each location of which has a count $>m$, is denoted as a patch. Similarly, a group of units, each of which has a count $<m$, is denoted as a gap. Units in patches and gaps are assigned subscripts, *i* and *j*, respectively; i.e., units with count $c_i > m$ are ascribed a cluster index, $z(\mathbf{p}) = \nu_i$, and units with count $c_j < m$ are ascribed a cluster index, $z(\mathbf{p}) = \nu_j$. In a random arrangement of counts, the expected value of the cluster index is one for a location within a patch, and -1 for a location within a gap; consequently, for a test of nonrandomness, the mean value over patch units, $\underline{\nu}_i$, is compared with 1 and the mean value over gap units, $\underline{\nu}_j$, is compared with -1. The index value, $\text{v}_{clusth} = 1.5$ (that is, 1.5 times the expected value in a random distribution), was adopted by Perry et al. (1999) and Perry and Dixon (2002) as an informal, heuristic threshold for significant clustering. In figures below that show patches of high listener-rated indicators, $z_{la}(\mathbf{p})$, contours were interpolated using Matlab gridding and contouring functions to designate areas within which $z_{la}(\mathbf{p}) > \text{v}_{clusth}$.

The index of aggregation is an overall measure of clustering (Perry et al. 1999), comparing the observed total distance to regularity with the mean from a series of random iterations (in these analyses, 5,967 iterations). The index of aggregation has an expected value of one for a random distribution and is considered significant if 95% of randomly permuted counts have a smaller distance to regularity.

Critical values of local association were estimated by SADIE with procedures described in Perry and Dixon (2002), with effects of autocorrelation adjusted by use of an effective sample size (Dutilleul 1993). The SADIE software tested the statistical significance of clustering and local spatial association by using 9,999 randomization distributions, X_{rand}, randomly permuting the counts or indicator variables among the sampled locations, and then recalculating the indices. The expected value of the local spatial association at site, *k*, is $\chi_k = 0$ in a random distribution of counts, and the overall spatial association is the mean of the local values, $X = \Sigma_{\text{k}} \cdot \chi_k / n$.

Results and Discussion

Auburn 1998 Soil Invertebrates. The sound-producing organisms excavated from the upper 15 cm of soil in the Auburn 1998 survey included millipedes (Diplopoda), white grubs (Coleoptera: Scarabaeidae), ground beetles (Coleoptera: Carabidae), earthworms (Annelida: Oligochaeta), and earwigs (Dermaptera). Sixteen of the 169 recording sites contained economically important white grubs [*Phyllophaga* spp., *Cyclocephala* spp., *Polyphylla* spp., and *Cotinis nitida* (L.)]. The mean density slightly exceeded the commonly accepted economic damage threshold of $50/\text{m}^2$ (Merchant and Crocker 1999). Six sites contained white grubs in combination with other sound-producing invertebrates of lesser economic importance (millipedes, ground beetles, wireworms, or earwigs), and

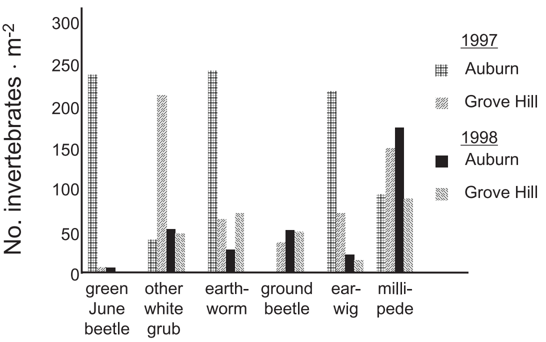

Fig. 1. Population densities of the most numerous invertebrates excavated from forage fields at Auburn and Grove Hill, AL, in 1997 and 1998.

51 sites contained only the invertebrates of lesser importance. No consistent pattern was evident in the occurrences of different soil invertebrates across the four surveys (Fig. 1).

Auburn 1998 Spectral Profiles. To distinguish valid soil invertebrate sounds from background noise, the spectrum of each sound pulse recorded in the Auburn-1998 survey was compared with spectral profiles (Mankin et al. 2000) constructed from samples of known origin (Fig. 2). A recorded sound pulse was considered valid if its duration was <5 ms and its least-squares difference from one of the three invertebrate profiles was smaller than the least-squares difference from either of the two background noise profiles in the frequency range between 100 and 3,000 Hz. As with the invertebrate sound pulse and background noise profiles in Mankin et al. (2000, 2001), all of the invertebrate profiles but none of the background noise profiles had significant energy between 600 and 1,500 Hz. The profile-comparison procedure eliminated much of the background noise, which tended to have peak energies below 300 Hz and was longer in duration than typical invertebrate-produced signals (Mankin et al. 2000).

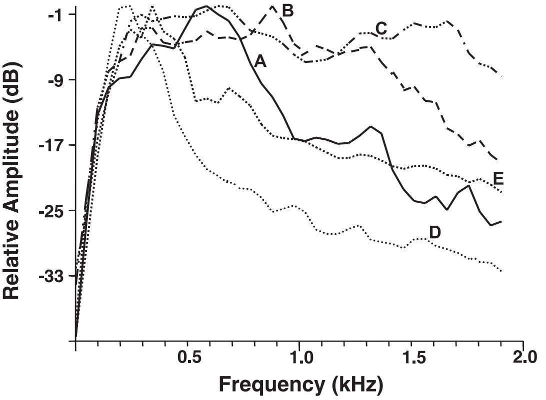

Fig. 2. Spectral profiles used to classify sound pulses in the Auburn 1998 survey: A, average spectrum of 367 sound pulses in a sample containing three green June beetles and one wireworm (Coleoptera: Elateridae); B, average spectrum of 101 pulses in sample with one masked chafer and one ground beetle; C, average spectrum of 125 pulses in sample with five millipedes; D, 20-s period of airplane noise; and E, average spectrum of 16 pulses in sample where no soil invertebrates were excavated.

The process of constructing the profiles used in the Auburn 1998 survey required multiple iterations of 1) screening recordings for series of acceptable pulses that could be used in constructing representative profiles, and 2) testing potential profiles against randomly selected invertebrate and background sounds. Initially, most of the potential profiles were discarded because they were either too selective or too unselective for reliable identification of valid pulses. Only a few of the files contained noise-free sections with enough pulses to provide a broadly representative invertebrate sound profile. In addition, extraneous sounds of many different types occurred in the background, which made it difficult to construct a representative background noise profile. Ultimately, we focused the profile analyses on recordings from two distinct sets of sites, the first set where white grubs or millipedes had been recovered and the second set where no insects were recovered but significant background noise of several different types was detected. The profiles with sound pulses produced by white grubs (Fig. 2A and B) were constructed to optimize detection of white grubs, which were the most economically important insects in the survey, and the profile with sound pulses produced by millipedes (Fig. 2C) was constructed to optimize detection of millipedes, which were the most common invertebrates in the survey.

The spectral profiles of the sound pulses produced by the different invertebrates in the Auburn-1998 survey overlapped considerably; consequently, it was not feasible to distinguish the species acoustically. In comparing acoustic assessments with excavations, we pooled the counts of all of the easily detected sound producers (millipedes, white grubs, ground beetles, and earwigs) into a single group, noisemakers. A site was counted as infested if one or more noisemakers were present in the excavated samples. Earthworms had been detectable and had been included in the Auburn 1997 and both Grove Hill surveys. However, perhaps because of low rainfall during the preceding month, sites with only earthworms present did not produce detectable activity, so earthworms were not included in the Auburn 1998 noisemaker category.

Survey-Specific Indicator Threshold Cutoffs. To maximize the correlations in the SADIE and contingency analyses between soil invertebrate counts and the sound-rate indicator variables, i_{sra} in equation 4, we set the sra_{low} threshold cutoff separately in each survey at a rate that maximized the number of uninfested sites and minimized the number of infested sites below the cutoff. The sra_{high} cutoff for each survey was set at a rate that minimized the number of uninfested sites and maximized the number of infested sites above the cutoff. In the Auburn 1998 survey, for example, 71 sites, mostly uninfested, had sound pulse rates ≤ 2 pulses · min^{-1}, and 30 sites, mostly infested, had ≥ 20

Table 1. Threshold cutoffs for sra_{low} and sra_{high} sound-pulse-rate indicator variables, and mean sound-pulse rates at the (*N*) infested sites

Survey	Threshold cutoff, sra_k (pulses · min^{-1})		Mean sound pulse rate (pulses · min^{-1})
	$k = low$	$k = high$	
Auburn 1998	2	20	18.57 ± 3.42 ($N = 67$)
Auburn 1997	2	35	52.40 ± 5.20 ($N = 104$)
Grove Hill 1998	30	52	46.96 ± 8.43 ($N = 75$)
Grove Hill 1997	10	30	18.15 ± 1.63 ($N = 130$)

pulses · min^{-1}. Thresholds derived by this procedure are listed in Table 1 for each survey, along with the mean infested-site sound pulse rates. The thresholds were lowest for Auburn 1998 and highest for Grove Hill 1998. Until more is known about the different biological and environmental factors that can affect these thresholds, the large range of values in Table 1 suggests that acoustic prediction will be most accurate if the thresholds are reset each time a new survey is conducted.

Auburn 1998 Geostatistical Analysis. Contour maps of the kriged estimates of sound-rate and noisemaker indicator variables are shown in Fig. 3A and B. Details of the semivariogram models used in the calculations are listed in Table 2. In several areas of the field, high values of the probability indicator on one map are congruent with high values of the noisemaker indicator on the other, and in other areas, low values are congruent with low values. In Fig. 3B, several high-high areas are marked in bold for later comparison with SADIE analyses. (Note: the specific coordinates, defined by [horizontal, vertical] distance in meters from left corner, are **a** = [84, 56], **b** = [35, 42], **c** = [140, 49], **d** = [63, 35], **e** = [84, 35], **f** = [98, 35], **g** = [42, 28], **h** = [63, 21], and **i** = [98, 14]). Two low-low

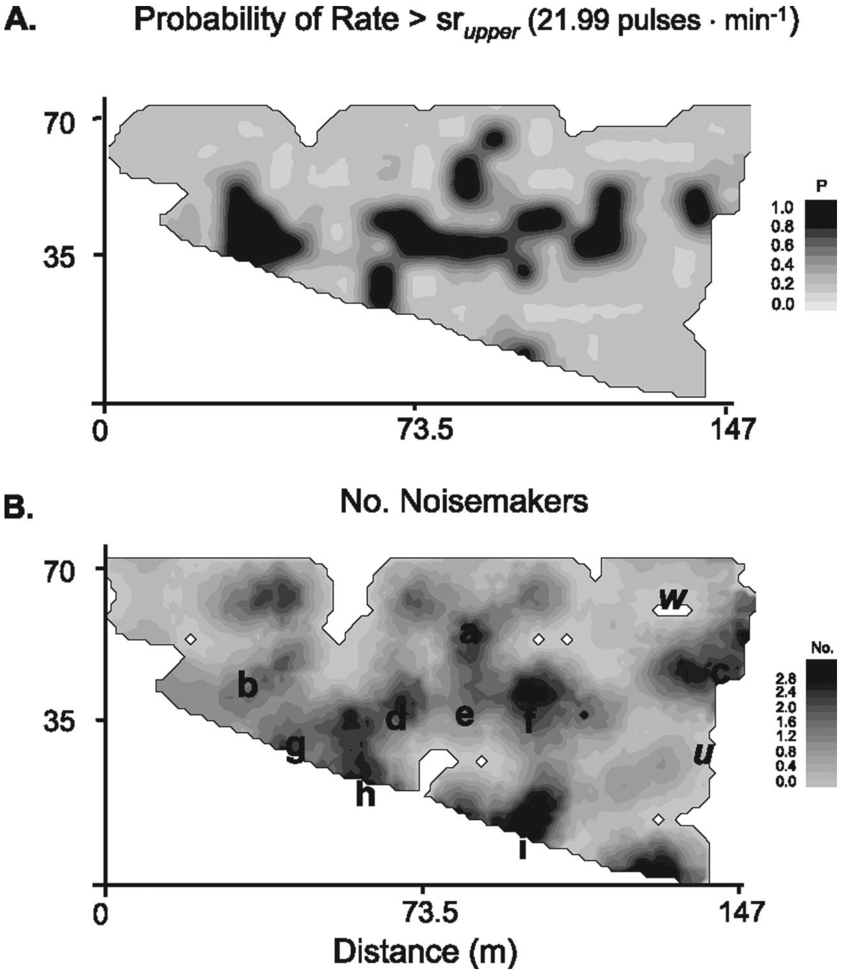

Fig. 3. Maps of Auburn 1998 kriging estimates of A, probability of occurrence of recording sites with noisemaker sound-rate indicator, $i_{sr} > \text{sr}_{upper} = 21.99$ pulses · min^{-1}, with darkest color indicating highest probability; B, distribution of noisemaker indicator variable, i_n, with darkest color indicating ≥3.0 noisemakers and lightest color indicating 0.0 noisemakers. White space indicates areas where estimates were not calculated. Details of the geostatistical models are listed in Table 2. For later reference in comparisons with SADIE analyses, letters, **a–i,** designate areas with high i_n and i_{sr}. Letters ***u*** and ***w*** designate areas with low i_n and i_{sr}.

Table 2. Semivariogram model types and parameters used in indicator kriging of sound pulse rate and noisemaker distributions in Auburn 1998 survey

Indicator variable threshold[a]	Type[b]	Nugget[c]	Range[d] (m)	Sill[e]	Modified Cressie goodness of fit[f]	Actual mean value	Est. mean value	Avg error statistic[f]
$Sr_{\text{lower}} = 10.01$	2Sph	0.0155	10.08	0.1104	0.0044	0.2959	0.3013	−0.0115
			15.847	0.0831				
$Sr_{\text{upper}} = 21.99$	Sph	0.0531	17.93	0.2281	0.0446	0.54	0.5725	−0.0441
$n_{\text{lower}} = 0.5$	Gau	0.16	5.121	0.08	0.008	0.3964	0.3964	−0.00037
$n_{\text{upper}} = 1.5$[g]	Sph	0.1518	10.552	0.1064	0.0005	0.4179	0.4133	0.0088

[a] See Equations 1 and 2 in Materials and Methods.

[b] Model types: Gau, Gaussian; Sph, Spherical; 2Sph, two-component Spherical (2 ranges and 2 sills).

[c] Nugget, variability at zero distance between sample points.

[d] Range, distance over which spatial correlation occurs.

[e] Sill, semivariance limit as distance between sample points becomes infinite.

[f] Smaller values of parameter indicate better correspondence of samples with model.

[g] The median value, 3, was used in converting the probability of more than one insect back to density estimates shown in Fig. 3 (see Materials and Methods).

areas are marked in bold italics: $\boldsymbol{w} = [126, 63]$ and $\boldsymbol{u} = [133, 28]$. The R^2 value for the correlation between the kriged estimates for sound-rate indicator, i_{sr}, and noisemaker indicator, i_n, was 0.41 ($t = 10.8$, df = 167, $P < 0.0001$). Based on the success of these correlations, we considered further applications of indicator variables in contingency analyses comparing acoustic and traditional estimates of infestation across surveys.

Contingency Analyses. Contingency analyses of the distributions of sound-rate and listener indicators of infestation likelihood (Table 3) revealed significant differences between indicator distributions at infested and uninfested sites in all of the surveys except Grove Hill 1997. The χ^2 value was larger for the differences in distributions of the listener indicators between infested and uninfested sites than for the sound-rate indicators. Part of this difference could be due to the capability of listeners to identify weak high-frequency snaps and scrapes that the sound-rate analysis does not always identify, particularly during periods of high background noise. This usually results in more of the infested sites being rated *high* by listener assessment than by sound-rate assessment. Such an effect also can be seen in Table 4, which considers the relationship between sound-rate and listener indicator variables across sites for all surveys. More than 65% of the sites assessed by listeners at a *high* likelihood of infestation were rated *medium* or *low* likelihood by the sound-rate assessment. Overall, however, there was strong correlation in Table 4 between listener and sound-rate assessments ($\chi^2 = 124.6$, df = 4, $P < 0.001$).

Table 3. Numbers of uninfested and infested sites assessed at different likelihoods of infestation by sound pulse rate and listener methods, and the χ^2 and probabilities (P) that distributions at uninfested and infested sites were independent of acoustic assessment

Assessed likelihood of infestation	Sound-pulse-rate assessment		Listener assessment	
	Uninfested	Infested	Uninfested	Infested
Auburn 1998	($\chi^2 = 9.32$, $P < 0.01$)		($\chi^2 = 22.06$, $P < 0.005$)	
Low	49	22	21	3
Medium	42	26	32	8
High	11	19	49	56
Auburn 1997	($\chi^2 = 9.00$, $P < 0.025$)		($\chi^2 = 26.44$, $P < 0.005$)	
Low	2	1	5	0
Medium	15	52	0	12
High	5	51	17	92
Grove Hill 1998	($\chi^2 = 6.21$, $P < 0.05$)		($\chi^2 = 13.54$, $P < 0.005$)	
Low	73	59	14	1
Medium	12	3	38	24
High	8	13	41	50
Grove Hill 1997	($\chi^2 = 4.84$, $P > 0.05$)		($\chi^2 = 5.34$, $P > 0.05$)	
Low	17	52	4	5
Medium	6	50	15	44
High	10	28	16	85

Sound-pulse-rate assessments of infestation likelihood are listed in Table 1 and listener assessments in Materials and Methods. All of the contingency analyses had 2 df.

Differences in the ratios of the mean sound pulse rates at infested sites to the threshold cutoff rates for *high* infestation likelihood suggest a partial explanation for the lack of significance of a relationship between acoustic and traditional assessments of infestation at Grove Hill in 1997. The mean infested-site rate was only 60.5% of the threshold for *high* likelihood of infestation in the Grove Hill 1997 survey (Table 1). In contrast, the Auburn-1998 survey had a mean infested site rate that was 92.9% of the threshold cutoff for *high* infestation likelihood, and the relationships between the observed and predicted infestations proved to be significant. Similarly, at Grove Hill in 1998, the mean rate was 90.3% of the threshold for *high* infestation likelihood, and in the Auburn 1997 survey, the mean rate was even higher, 148% of the *high* threshold. These results suggest that an assessment of the level of soil invertebrate activity in relation to background

Table 4. Comparison of the numbers of sites in all surveys with sound pulse rate indicators assessed at *low*, *medium*, or *high* likelihood of infestation when listener indicators were assessed *low*, *medium*, or *high*

Sound-rate assessment	Listener assessment		
	Low	*Medium*	*High*
Low	46	115	119
Medium	8	50	149
High	0	9	137

Sound rate and listener indicator variables are designated as in Table 3.

Table 5. Cluster and aggregation indices and their probabilities (*P*) for noisemaker counts and acoustic indicators of infestation likelihood at survey sites

Sampled count or indicator	Mean cluster index for		Index of aggregation (*P*)
	Gaps, $\underline{v}_j$ (*P*)	Patches, $\underline{v}_i$ (*P*)	
Auburn 1998			
Noisemaker count	−1.063 (0.3213)	1.088 (0.2826)	1.020 (0.3694)
Sound-rate indicator	−1.600 (0.0141)	1.455 (0.0268)	1.551 (0.0206)
Listener indicator	−1.586 (0.0102)	1.629 (0.0096)	1.660 (0.0106)
Auburn 1997			
Noisemaker count	−1.628 (0.0154)	1.511 (0.0307)	1.732 (0.0127)
Sound-rate indicator	−1.763 (0.0075)	1.918 (0.0037)	1.913 (0.0037)
Listener indicator	−1.743 (0.0111)	1.827 (0.0065)	1.795 (0.0087)
Grove Hill 1998			
Noisemaker count	−1.329 (0.0354)	1.212 (0.0781)	1.333 (0.0384)
Sound-rate indicator	−1.183 (0.1130)	1.236 (0.0669)	1.185 (0.1081)
Listener indicator	−1.034 (0.3357)	1.010 (0.4039)	1.182 (0.1111)
Grove Hill 1997			
Noisemaker count	−1.124 (0.1842)	1.218 (0.0747)	1.156 (0.146)
Sound-rate indicator	−1.246 (0.0682)	1.258 (0.0545)	1.254 (0.0602)
Listener indicator	−1.515 (0.0023)	1.552 (0.0020)	1.536 (0.0037)

noise can help determine whether the use of an acoustic indicator method is feasible in a given survey. In cases where cool temperatures, drought, or physiological factors cause the mean sound pulse rate to drop below the background noise level, acoustic methods may be unreliable. Likewise, acoustic methods may be unreliable under conditions of high background noise. In this study, the soil temperatures and soil characteristics were similar across surveys (see *Materials and Methods*), and the mean infested site sound pulse rate was similar in the Clark 1997 and Auburn 1998 surveys (Table 1). However the threshold for low likelihood of infestation was much higher in the Clark 1997 survey than in Auburn 1998 survey, due to a higher level of wind and other background noise. This suggests background noise was the major contributor to the decreased accuracy of acoustic detection in the Clark 1997 survey.

SADIE Analyses. Cluster indices for noisemaker and acoustic indicator variables were calculated for all of the surveys, and the local associations between noisemakers and acoustic indicators at individual survey sites were estimated from the clustering indices by SADIE by using equation 5. The mean cluster indices for noisemaker patches and gaps are listed in Table 5, along with the mean cluster indices for sound-rate and listener indicators of infestation likelihood and the overall indices of aggregation for each survey. The Auburn 1997 survey had the greatest number of significantly clustered indicators (all six cluster means and all three overall indices of aggregation were significantly different from those of the randomization distribution, X_{rand}). Grove Hill 1998 had the lowest number of significantly clustered variables (the mean index of noisemaker gaps and the overall index of aggregation for noisemakers were significantly different from those of randomly permuted counts). These two results are not surprising, considering that the largest, most active soil invertebrates, the green June beetles, were most prevalent in the Auburn 1997 survey (Fig. 1), and the fewest soil invertebrates were found in the Grove Hill 1998 survey. All of the surveys except Grove Hill 1998 had a statistically significant overall association between noisemaker counts and the listener indicator of infestation likelihood (Table 6).

Distributions of clustering and local spatial associations for noisemaker counts and acoustic indicators of infestation likelihood are plotted in Fig. 4 and 5 for Auburn and Grove Hill, respectively. Individual sites were marked with different symbols determined by the value of the cluster index for noisemaker counts, $z_n(\mathbf{p})$, relative to the Perry et al. (1999) threshold for significant clustering, $v_{clusth} = 1.5$. Sites were marked also where the local association between noisemaker counts and acoustic indicators, $\chi_{n,la}(\mathbf{p})$ or $\chi_{n,sra}(\mathbf{p})$, exceeded the 97.5th centile critical value (Table 6). Different shadings indicate areas where z_{la}, the listener-indicator cluster index, was interpolated to be $>$ or $\leq v_{clusth} = 1.5$. The interpolations were performed using the Matlab coutourf function. Because the lis-

Table 6. Local and overall association between spatial patterns of noisemaker counts and acoustic indicators of infestation likelihood at survey sites

Associated indicator (effective *n*)[a]	Local spatial association				Overall spatial association (*P*)
	Critical value for centile		No. exceeding centile		
	2.5th	97.5th	Negative[b]	Positive[c]	
Auburn 1998					
Sound-rate, $\chi_{n,\ sra}$ (157.3)	−2.0764	2.0403	1	10	0.3454 (<0.001)
Listener, $\chi_{n,\ la}$ (169)	−1.9992	1.9763	0	6	0.2909 (<0.001)
Auburn 1997					
Sound-rate, $\chi_{n,\ sra}$ (126)	−1.951	1.9615	2	11	0.3037 (<0.001)
Listener, $\chi_{n,\ la}$ (126)	−1.945	1.9726	0	5	0.3592 (<0.001)
Grove Hill 1998					
Sound-rate, $\chi_{n,\ sra}$ (152.2)	−2.1194	2.055	7	9	−0.0351 (0.6613)
Listener, $\chi_{n,\ 1a}$ (152.1)	−2.1206	2.053	6	9	−0.0355 (0.6628)
Grove Hill 1997					
Sound-rate, $\chi_{n,\ sra}$ (135.4)	−2.2063	2.1985	4	7	0.1316 (0.0645)
Listener, $\chi_{n,\ la}$ (162.4)	−2.0547	2.0209	3	6	0.1667 (0.0168)

[a] Effective sample size estimated from the Dutilleul (1993) correction for spatial autocorrelation.

[b] Number of occurrences of local association <2.5th centile of randomization distribution, i.e., strong dissociation.

[c] Number of occurrences of local association >97.5th critical centile of randomization distribution, i.e., strong association.

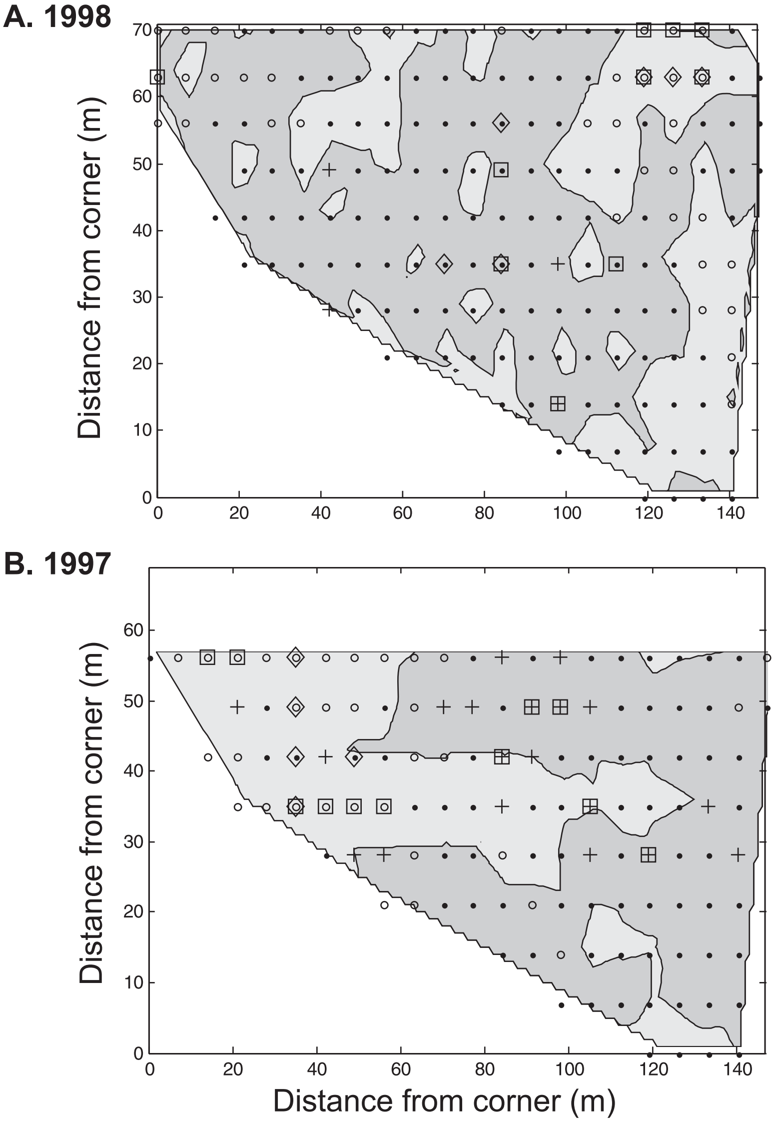

Fig. 4. Distributions at Auburn in (A) 1998 and (B) 1997 of clustering and local spatial associations for noisemaker counts and acoustic indicators: open circles designate where the cluster index for noisemaker counts, $z_n(\mathbf{p}) < -1.5$, filled circles designate where $-1.5 \le z_n(\mathbf{p}) \le 1.5$; and + symbols designate where $z_n(\mathbf{p}) > 1.5$. Areas where the interpolated values of cluster indices for listener indicator, $z_{la}(\mathbf{p})$, exceeded $v_{clusth} = 1.5$ are designated by the darkest contours. Diamonds and squares designate where the 97.5th centile of the randomization distribution (Table 6) is exceeded by listener or sound-rate local spatial associations, $\chi_{n,la}(\mathbf{p})$ or $\chi_{n,sra}(\mathbf{p})$, respectively.

tener and sound-rate indicators were highly correlated (Table 4), only the listener indicators are shown in Figs. 4 and 5.

Although they are estimated by different procedures, the distributions in Figs. 4A and 3B have several notable areas of congruence. The four sites marked as **a**, **d**, **e**, and ***w*** in Fig. 3B, for example, exceeded the 97.5h centile critical value for local association between noisemaker counts and listener indicators, and they also were sites where the kriged estimates of the noisemaker and sound rate indicators had been congruent. The cluster index for noisemaker counts exceeded the Perry et al. (1999) threshold for significant clustering, v_{clusth}, at locations in 4A congruent to three sites with high i_n, **e**, **g**, and **i**, in Fig. 3B. Similarly, the cluster index for noisemaker counts indicated gaps were present at locations in 4A congruent to two sites with low i_n, ***u***, and ***w***, in Fig. 3B. The cluster index for the listener indicator, $z_{la}(\mathbf{p})$, in Fig. 4A was congruent with sites of high i_n at **a**–**i**, as well as with sites of low i_n, ***u*** and ***w***, in Fig. 3B.

Numerous areas can be seen in Fig. 4B and Fig. 5A and B where congruence occurred between patches of noisemakers and patches of listener indicators, and

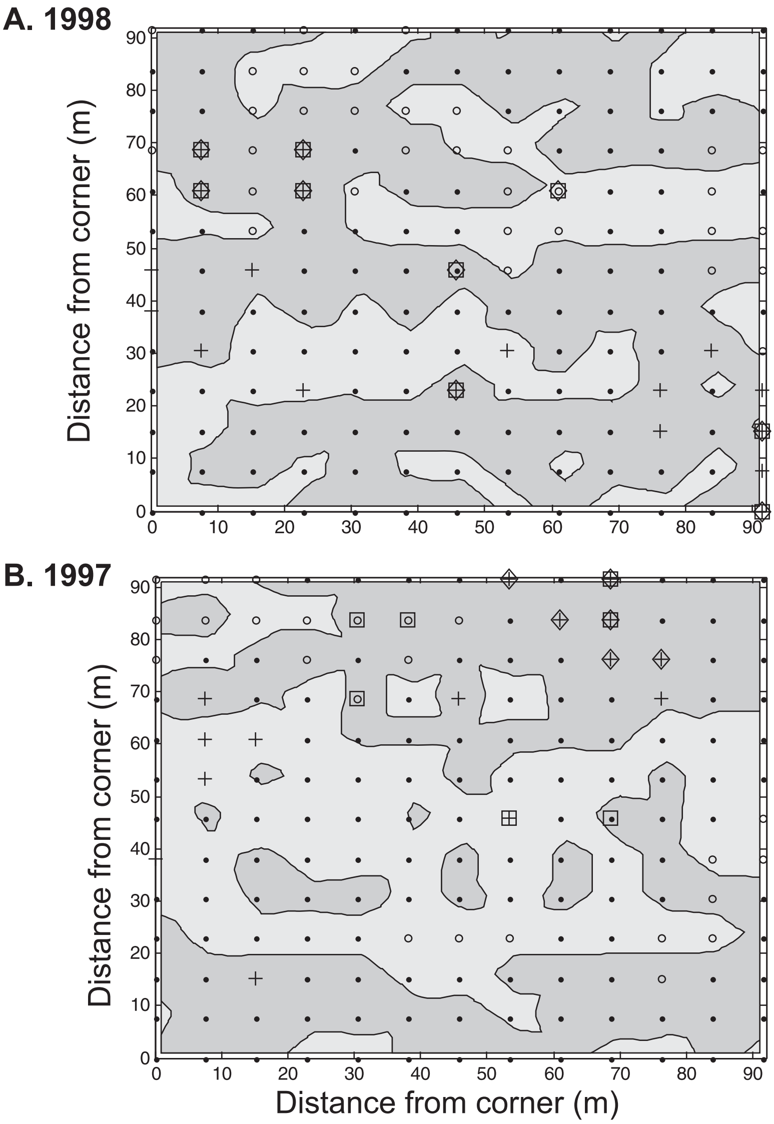

Fig. 5. Distributions at Grove Hill in (A) 1998 and (B) 1997 of clustering and local spatial associations for noisemaker counts and acoustic indicators. Symbols and contours are as designated in Fig. 4.

there are numerous areas of significant local association between noisemaker counts and acoustic indicators. Significant local associations were found between patches of noisemakers and acoustic indicators as well as gaps of noisemakers and acoustic indicators, as indicated by diamonds and/or squares at sites marked

Table 7. Targeting ratios of noisemaker and white grub counts at sites in the highest 20th centiles of acoustic-indicator cluster indices, compared with ideal ratios calculated from the actual counts of noisemakers and white grubs in the 20th centiles of their respective highest count sites

Survey	Noisemaker targeting ratio			White grub targeting ratio		
	Ideal	Sound-rate	Listener	Ideal	Sound-rate	Listener
Auburn 1998	4.130	0.763	2.026	5.000	2.000	0.500
Auburn 1997	2.400	1.182	1.420	4.035	1.140	2.280
Grove Hill 1998	3.435	1.007	0.858	5.000	1.341	1.220
Grove Hill 1997	2.530	1.011	1.022	2.885	0.943	1.143
Mean (SE)	3.12 (0.40)	0.99 (0.09)	1.33 (0.26)	4.23 (0.50)	1.36 (0.23)	1.29 (0.37)

Targeting ratio = (sum of counts in the 20th centile of highest values of cluster index) / (total of expected counts in the same no. of randomly selected sites); see Results.

also by + or an open circle. It is notable also that one or more sites in each survey had statistically significant associations between noisemaker counts and both sound rate and listener indicators of infestation likelihood (indicated by a square and diamond at the same site). These results provide strong evidence that indicator variables can be useful interpretive tools for analyses of correlations between traditional and acoustic estimates of soil invertebrate infestations.

Application of Cluster Index Maps for Targeting of Infestations. A goal of many soil invertebrate surveys is to target control treatments to restricted areas that contain the greatest densities of pests (Midgarden et al. 1997, Fleischer et al. 1999). The distributions of sound rate indicators in Fig. 3A or cluster indices of the listener-assessed infestation likelihood indicators in Figs. 4 and 5, for example, could be used to identify and treat areas of highest estimated density. We considered whether limited targeting of sites with the highest values of cluster indices for acoustic assessments of infestation likelihood would have provided improved treatment of the white grubs in this study compared with nontargeted treatments of the same number of sites. An example was selected of a limited targeting of 20% of the total area in each survey. To obtain comparisons of targeted and random treatments, targeting ratios were calculated by summing the numbers of white grubs at sites in the highest 20th centile of cluster indices for acoustic indicators, and then dividing by the expected count in a treatment of the same number of randomly selected sites, i.e., 0.2 T_{wg}, where T_{wg} was the total of the white grub counts in the survey. Because the cluster indices were based on all noisemakers, not just white grubs, we considered the targeting ratios for noisemakers as well. Ideal targeting of white grubs and noisemakers was estimated by summing the counts of white grubs and noisemakers at sites in the highest 20th centiles of white grub and noisemaker counts, respectively.

Approximately 30% more white grubs were targeted by the acoustic cluster indices than would be expected from randomly selected samples (Table 7). The mean white grub targeting ratios were slightly higher than the noisemaker ratios, possibly because the white grubs were more clustered than the noisemakers and the large, actively feeding white grubs were easier to detect acoustically than many of the noisemakers of lesser economic importance. The practical importance of the higher targeting level would depend on the relative costs of treatment compared with targeting and, in general, all targeting is more effective when the population to be treated is clustered rather than uniform, as at Auburn in both years and Grove Hill in 1998. Similarly the potential effectiveness of acoustically targeting reserves for reduced or eliminated use of pesticides, either to avoid buildup of resistance (Midgarden et al. 1997) or to conserve natural enemies (e.g., Koppenhöfer et al. 2000, Rogers and Potter 2003), would be most effective in areas with a strongly inhomogeneous distribution of white grubs.

Acknowledgments

Robert Hickling (Sonometrics, Huntington Woods, MI) provided the soil microphone system. Zandra DeLamar, David Gaylor, Ryan Anderson, Andrew Nixon, Aubrey Davis, Stephen Hartsfield, and Abhishek Battacharyya (Auburn University) assisted in data collection. Everett Foreman, Betty Weaver, and Eric Kaufmann (USDA–ARS Center for Medical, Agricultural, and Veterinary Entomology, Gainesville, FL) assisted with signal analysis. Thanks to Joseph Perry for providing the SADIE software, to Jerry Matthews for allowing us to sample in his field in Clarke County, AL, and to two anonymous reviewers who provided thoughtful comments on a previous version of the report. This research was supported in part by the Cooperative State Research Education and Extension Service, U.S. Department of Agriculture, under Agreement 58-6615-8-013. Funds for this project also were made available from the Citrus Production Research Marketing Order by the Division of Marketing and Development, Florida Department of Agriculture and Consumer Services, Bob Crawford, Commissioner.

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Received 12 November 2006; accepted 14 January 2007.