Mapping of Soil Insect Infestations Sampled by Excavation and Acoustic Methods

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ABSTRACT Geostatistical analysis was used to map traditionally and acoustically sampled populations of soil invertebrates at two different times in a hayfield at Grove Hill, AL, and once in an Auburn, AL, hayfield. The distributions of nearly all the soil invertebrates and their sounds were nonrandom in all three mapping studies. The maps constructed by excavation and acoustic sampling methods were compared by correlating the estimated (kriged) soil invertebrate counts with the estimated (kriged) counts of sounds per minute (pulse rate). Acoustic and traditional estimates were positively correlated in the Auburn study. Kriged estimates for green June beetle grub counts overlapped significantly with kriged estimates of sound pulse rate ($R^2 = 0.47$). Overlap with sound pulse rates increased slightly when other soil organisms were counted along with green June beetle grubs: estimates of sound pulse rates were significantly correlated with counts of all white grubs ($R^2 = 0.50$), all white grubs with earthworms ($R^2 = 0.52$), all white grubs with earthworms and earwigs ($R^2 = 0.59$), and total invertebrates ($R^2 = 0.59$). The correlation between acoustic and traditional estimates was not significant at Grove Hill in either year, possibly because of a lack of experience in signal analysis or because the soil invertebrates may not have generated enough sounds to be detected above the background noise levels. These results suggest that acoustic technology is a promising tool for detecting insect pests in soil, but that further study and additional analysis are needed to improve interpretation of acoustic data obtained in the field.

KEY WORDS soil insects, acoustic sampling, geostatistics

SOIL-DWELLING INSECT PESTS cost the agriculture industry billions of dollars yearly in damaged crops and maintenance costs; moreover, these insects are difficult to control because they are concealed in the soil (Crocker et al. 1995, Riley et al. 1997, Vittum et al. 1999). Because they cannot be seen, invertebrates in the soil are traditionally sampled and mapped by excavating soil at several sample sites (usually with a soil corer or similar device) and mechanically extracting the invertebrates from soil by removal of the root mass, dry sieving, soap flushing, or heat extraction (Southwood 1978, Cobb and Mack 1989, Villani and Wright 1990). These methods are time-consuming and expensive. They are destructive to crops or turf when large numbers of samples are collected (Potter and Braman 1991, Potter 1993). New detection tools and methods of analysis are needed to locate infestations and to plan and implement integrated pest management (IPM) programs necessary for proper control. The use of new mapping tools such as geostatistics and geographic information systems (GIS) (Liebhold et al. 1993) and the development of less expensive, nondestructive sampling procedures can all play a role in improving IPM of soil insects.

Geostatistical analysis uses distances between samples and sample values to evaluate spatial structure (Schotzko and O'Keefe 1989, Davis 1994). One method of describing spatial dependence is to estimate a semivariogram and fit a model. A semivariogram describes spatial dependence among samples by plotting the sample variances of the sample pair differences against the distance between sampling points. Once a model is obtained, the data can be estimated (kriged) based on the model. Kriging is used to produce the best estimate of an unknown value of a parameter at some location within a sample area or plot (Cressie 1986, Marx and Thompson 1987).

Only a few nondestructive techniques for detecting insects in soil have been reported or are in present development. Radiography (x-ray) was used in the laboratory to study the movement and feeding behavior of four species of grubs that are pests of turfgrass (Villani and Wright 1990). Acoustic methods adapted from previous studies with stored product insects in grain (Shuman et al. 1993, Hagstrum et al. 1996, Mankin et al. 1997) have been used to detect soil insects in the laboratory (Mankin et al. 2000), but until now

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these methods have not been tested extensively in the field. Acoustic methods also have been used to detect termites in wood structures (Scheffrahn et al. 1993, Lemaster et al. 1997).

The objective of this study was to collect and compare information about the spatial distribution of insect infestations in hayfields obtained by excavation and acoustic sampling methods. From previous studies (e.g., Southwood 1978), it was expected that the soil insects would be distributed nonrandomly. Geostatistical tools were used to map and compare the distributions of soil insects and sounds.

Materials and Methods

In 1997–1998, two perennial grass hayfields (mixed Bermuda grass and bahiagrass) with sandy-loam soil in Alabama were used for sampling. Sampling for soil insects was performed in late August and early September in Grove Hill (Clarke County, AL, 1997–1998) and in Auburn (Lee County, AL, 1997). Most white grubs have likely hatched and are feeding at this time of year. Grid sampling was used in both fields, with sample points 7.0–7.6 m apart. A differential global positioning system (DGPS) was used to identify the geographical location of each sample point. All DGPS systems located the points with an accuracy of 1 m or better. After marking the sample points, acoustic samples were taken with a microphone and then soil was collected at the same sample point. Insects and other invertebrates were extracted from the soil, counted, and preserved in 70% ethanol.

Auburn, 1997. The Vision System Software/GPS package was used to space 126 sample points 7.0 m apart on a grid to fit within a 0.5-ha plot (Rockwell Collins Incorporated 1998). A TASCAM digital audio tape recorder (model DA-P1, TASCAM, Montebello, CA) was used to record sounds detected by an electret microphone developed by Robert Hickling (Sonometrics, Huntington Woods, MI). The microphone was inserted into the ground, with the recording membrane at a depth of 7.5 cm. Recordings were made for 180 s at each sample point. Soil was excavated by taking two soil cores (10 cm diameter, 15 cm deep) from each sample point on either side of the microphone slit.

Grove Hill, 1997. The location of 169 sample points in Grove Hill was determined by pulling measuring tapes from one corner of the grid and marking the units at 7.6-m intervals in a 91.4-m-square grid (0.8 ha). The geographic location of the points was logged with the OmniLog software, using the Omnistar National Differential GPS System, the Omnista 7000 DGPS receiver, and a palm-top computer (Omnistar Incorporated 1996). Acoustic samples were recorded in the same way as the Auburn site. Soil was excavated by digging a 20.3-cm cube of soil with a square spade around the point where the sound was recorded.

Grove Hill, 1998. The geographic location of the same 169 sample points was logged with the Farm GPS software (Red Hen Systems 1996) (which uses the MapInfo platform), using the Omnistar National Differential GPS System, the Omnistar 7000 DGPS receiver, and a ruggedized Pentium-based lap-top computer. Acoustic and soil samples were collected as in Grove Hill in 1997.

Point Mapping. Point maps, showing actual numbers of soil invertebrates found and actual sound pulse rates at each sample point, were produced with the MapInfo Professional software package (MapInfo Corporation 1998).

Sound Analysis. Custom-written software, and a personal computer were used for spectral and temporal analysis of recordings (Embree and Kimble 1991, Mankin 1994). Spectral profiles of soil invertebrate sounds and background noise were developed and used to count the invertebrate sounds in the samples. The detailed procedures for spectral and temporal analysis and development of soil invertebrate sound and background noise spectral profiles are explained in Mankin et al. (2000) and Mankin et al. (2001). In brief, signals with peaks exceeding a user-adjustable minimum threshold were passed to an analysis subroutine for further processing. Sounds were considered to be ended when the signal level fell below threshold for at least 10 ms. A spectrum was calculated for a 3-m (512-data-point) segment (pulse) centered on each peak. The spectrum was compared with insect and background noise profiles derived from recordings where the soil organisms were verified by excavation. Sound pulses that were too long in duration or that failed to match an insect sound profile were discarded.

Because the recordings were obtained under typical field conditions, many recordings contained periods with wind noise, vehicle noise, and extraneous sounds. The computer software had difficulty screening out loud extraneous sounds effectively, but these could usually be identified easily by an experienced listener with headphones. Such periods were deleted from the analysis whenever they were identified. For this study, we did not attempt to acoustically distinguish among sound pulses made by different soil invertebrates. We counted a sound as valid if it matched any profile in the soil invertebrate sound spectral profile library (Mankin et al. 2000, 2001). The total number of sound pulses that matched a soil invertebrate sound spectral profile was divided by the total analysis period to calculate the rate of valid soil invertebrate sound pulses per minute (pulse rate) for later use in analyses.

Thresholds below which the sound pulse rates were not distinguishable from background noise were applied to the acoustic data. Thresholds were set at 10 sound pulses per minute for Grove Hill in 1997, 36 pulses per minute for Grove Hill in 1998, and 27 pulses per minute for Auburn in 1997.

Geostatistical Analysis. Geostokos Toolkit (Clark 1996) was used to analyze the spatial distribution of the soil invertebrate and sound counts. The analysis included fitting a model to semivariograms and kriging the data based on the models. Semivariograms were produced for each group of soil invertebrates and for sound pulse rates. The semivariograms determined if the data were spatially correlated. Additionally, some

Table 1. Semivariogram models of sound pulse rate and soil invertebrates from a perennial grass hayfield in Auburn, AL, 1997

Variable	Actual mean value[a]	Estimated mean value[a]	Average error statistic[b]	Model type	Nugget	Range, m	Sill	Slope[c]
Sound pulse rate	1.85	1.86	−0.008	Spherical	2.90	22.9	0.77	—
White grubs	0.26	0.25	0.009	Spherical	0.12	27.4	0.08	—
Chafers	0.04	0.04	0.000	Spherical	0.02	36.6	0.01	—
Green June beetles	0.23	0.22	0.009	Spherical	0.12	22.9	0.04	—
Wireworms	0.03	0.03	0.003	Linear	0.01	—	—	0.00003
Billbugs	0.01	0.01	0.005	Linear	0.004	—	—	0.00002
Millipedes	0.07	0.07	0.000	Linear	0.06	—	—	0.0004
Earthworms	0.23	0.24	−0.017	Spherical	0.13	30.5	0.08	—
Earwigs	0.22	0.22	−0.015	Spherical	0.12	30.5	0.04	—
Earthworms + all white grubs	0.47	0.48	−0.009	Linear	0.24	—	—	0.0006
Earthworms, all white grubs, and earwigs	0.63	0.63	−0.012	Spherical	0.19	42.7	0.15	—
Total soil invertebrates	0.70	0.70	−0.008	Linear	0.29	—	—	0.0007

[a] Data were transformed to $\log_{10}(x+1)$ prior to analysis. Actual mean value and estimated means were not significantly different at $\alpha = 0.10$. A model that fits properly would generate an estimated mean value equal to the actual mean value, and the average error statistic would equal 0.
[b] Average error of estimated values.
[c] For linear models only.

invertebrate groups that were thought to be more economically important or to make more noise than the other soil invertebrates were placed together in a single group for modeling. Counts of groups of invertebrates and sound pulse rates were $\log_{10}(x + 1)$ transformed to normalize the data. Only one variable, sound pulse rates for Grove Hill in 1998, did not improve with transformation. Therefore, that variable was not transformed.

Models (best-fit lines or curves) were fit to the semivariograms and the data were kriged, based on these models, to determine spatially related patches of data. Cross-validation was used to determine if the models were appropriate. The kriged estimates were imported into Surfer 7 surface mapping software (Golden Software Incorporated 1999) to produce contour maps.

Correlation analysis was used to determine if data obtained by soil excavation and sound data were spatially correlated (SAS Institute 1988). A correlation was deemed to be statistically significant if the P value was <0.05. A correlation was determined to be biologically significant if the R^2 value exceeded 0.4.

Results

Soil invertebrates found in the samples included wireworms (Coleoptera: Elateridae), billbugs (Coleoptera: Curculionidae), ground beetles (Coleoptera: Carabidae), millipedes (Diplopoda), earthworms (Annelida: Oligochaeta), masked chafers, *Cyclocephala* spp. (Coleoptera: Scarabaeidae), green June beetles, *Cotinis nitida* (L.) (Coleoptera: Scarabaeidae), *Phyllophaga* spp. (Coleoptera: Scarabaeidae), and *Polyphylla* spp. (Coleoptera: Scarabaeidae). Billbugs and green June beetles were not found in Grove Hill in 1998. Ground beetles, *Phyllophaga* spp., and *Polyphylla* spp. were not found in Auburn in 1997. Very few white grubs were found in Grove Hill in 1998, compared with the same site in 1997 or with Auburn in 1997 (Tables 1–3). Groups of invertebrates placed together based on economic importance or potential of making significant noise were all white grubs (green June beetles, masked chafers, *Phyllophaga* spp., and *Polyphylla* spp. grubs); all white grubs and earthworms; all white grubs, earthworms and ground beetles; and all white grubs, earthworms, ground beetles, and earwigs. Ants and surface-dwelling plant bugs, occasionally collected in the samples, were not included in the analysis.

Spherical or linear models were fit to semivariograms of all groups that showed a nonrandom spatial relationship (Tables 1–3). Cross-validation of the models for Grove Hill and Auburn indicate that all models were properly fit. The range within which there was correlation varied from 15.8 m (*Polyphylla* spp. from Grove Hill in 1998) to 140 m (earthworms, white grubs, and ground beetles from Grove Hill in 1997) (Fig. 1). The lower ranges indicate that points are correlated only with points in close proximity, and the higher ranges indicate that points are correlated at a much farther distance.

In some cases, semivariograms showed that a particular variable was randomly distributed: green June beetles in Grove Hill in 1997; and all white grubs, ground beetles, *Phyllophaga* spp., earwigs, and the group consisting of all white grubs, earthworms, earwigs, and ground beetles in Grove Hill in 1998. Spatial models were not fit to these data. Therefore kriged estimates of these data were not made.

Spatial patterns are not very distinct when looking at the maps displaying actual invertebrate counts or sound pulse rates for each point (Fig. 2). However, clusters of invertebrates or sounds are clearly visible in the contour maps of kriging estimates. The geostatistical analysis procedure has proven, in this experiment, to be a valuable tool in determining soil invertebrate distribution and recognizing areas of infestation. Without the maps of estimated values, the

Table 2. Semivariogram models of sound pulse rate and soil invertebrates from a perennial grass hayfield in Grove Hill, AL, 1997

Variable	Actual mean value[a]	Estimated mean value[a]	Average error statistic[b]	Model type	Nugget	Range m	Sill	Slope[c]
Sound pulse rate	1.44	1.44	0.003	Spherical	1.72	78.0	0.43	—
All white grubs	0.57	0.57	0.007	Spherical	0.21	47.5	0.08	—
Chafers	0.13	0.13	0.001	Spherical	0.08	31.7	0.02	—
Phyllophaga spp.	0.31	0.31	0.008	Spherical	0.18	78.0	0.02	—
Polyphylla spp.	0.09	0.09	0.004	Spherical	0.06	78.0	0.01	—
Wireworms	0.18	0.18	0.980	Spherical	0.11	31.7	0.02	—
Billbugs	0.04	0.04	0.014	Spherical	0.002	31.7	0.01	—
Ground beetles	0.09	0.10	0.012	Spherical	0.06	18.9	0.01	—
Millipedes	0.28	0.28	0.012	Spherical	0.20	31.7	0.08	—
Earthworms	0.16	0.16	0.003	Linear	0.10	—	—	0.0001
Earwigs	0.17	0.17	0.014	Spherical	0.10	23.8	0.05	—
Earthworm + all white grubs	0.69	0.69	0.007	Spherical	0.24	104.0	0.06	—
Earthworm + all white grubs + ground beetles	1.39	1.40	0.008	Spherical	0.06	140.0	0.12	—
Earthworms, all white grubs, ground beetles, and earwigs	0.85	0.86	0.014	Spherical	2.00	104.0	0.95	—
Total soil invertebrates	1.10	1.11	0.020	Spherical	0.27	104.0	0.14	—

[a] Data were transformed to $\log_{10}(x+1)$ prior to analysis. Actual mean value and estimated means were not significantly different at $\alpha = 0.10$. A model that fits properly would generate an estimated mean value equal to the actual mean value, and the average error statistic would equal 0.
[b] Average error of estimated values.
[c] For linear models only.

clusters of invertebrates or sound pulses would not have been as easily detected.

Kriged estimates were also valuable in determining if two variables were spatially related. When the individual point data were used, soil invertebrate populations and sound pulse rates were not significantly correlated. There were also no correlations between different kinds of soil invertebrates found.

In Auburn 1997, kriged estimates of sound pulse rates were positively correlated ($P \leq 0.0001$) with green June beetles ($R^2 = 0.47$), all white grubs ($R^2 = 0.50$), all white grubs and earthworms ($R^2 = 052$), all white grubs, earwigs, and earthworms ($R^2 = 0.59$), and total invertebrates ($R^2 = 0.59$) (Figs. 3 and 4). Using kriged estimates, earwigs were positively spatially correlated ($P \leq 0.0001$) with other invertebrates: masked chafers ($R^2 = 0.44$), green June beetles ($R^2 = 0.46$), all white grubs ($R^2 = 0.50$), and all white grubs and earthworms ($R^2 = 0.43$). Estimated numbers of wireworms were positively correlated ($P \leq 0.0001$) with millipedes ($R^2 = 0.77$) and were negatively correlated ($P \leq 0.0001$) with estimated green June beetle grubs ($R^2 =$ (0.41).

There were no correlations ($P > 0.05$) between kriged estimates of sound pulse rates and any invertebrate groups from Grove Hill in 1997. There were significant correlations between certain invertebrate groups. At Grove Hill in 1997, millipedes were posi-

Table 3. Semivariogram models of sound pulse rate and soil invertebrates in a perennial grass hayfield in Grove Hill, AL, in 1998

Variable	Actual mean value[a]	Estimated mean value[a]	Average error statistic[b]	Model type	Nugget	Range, m	Sill	Slope[c]
Sound pulse rate[d]	20.83	20.83	−0.000	Spherical	3150	23.8	400	—
Chafers	0.01	0.01	0.008	Spherical	0.006	47.5	0.007	—
Polyphylla spp.	0.02	0.02	0.003	Spherical	0.011	15.8	0.002	—
Wireworms	0.26	0.27	−0.017	Spherical	0.130	18.3	0.033	—
Millipedes	0.17	0.18	−0.012	Spherical	0.170	18.3	0.015	—
Earthworms	0.16	0.17	−0.009	Spherical	0.102	31.7	0.036	—
Earthworms + all white grubs	0.29	0.30	−0.012	Spherical	0.210	23.8	0.010	—
Earthworms + all white grubs + ground beetles	0.40	0.41	−0.121	Linear	0.255	—	—	0.0002
Total soil invertebrates	0.74	0.76	−0.026	Linear	0.370	—	—	0.00006

[a] Data were transformed to $\log_{10}(x+1)$ prior to analysis. Actual mean value and estimated means were not significantly different at $\alpha = 0.10$. A model that fits properly would generate an estimated mean value equal to the actual mean value, and the average error statistic would equal 0.
[b] Average error of estimated values.
[c] For linear models only.
[d] This variable was not log-transformed.

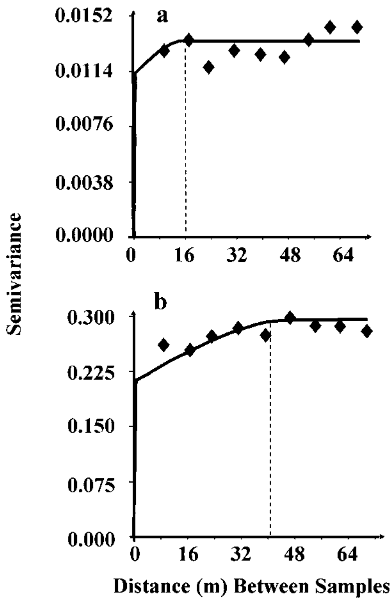

Fig. 1. Semivariograms for (a) *Polyphylla* spp. from Grove Hill, AL, in 1998, and (b) all white grubs from Grove Hill, AL, in 1997. Based on $\log(x + 1)$-transformed data. These semivariograms show the examples of the range at which the insects were correlated in this experiment. *Polyphylla* spp. from Grove Hill, AL (1998) have a range of 15.8 m and all white grubs from Grove Hill, AL (1997) have a range of 41.7 m. Other model parameters: (a) spherical model, nugget effect 0.0111, no. components = 1, sill = 0.0024, and modified Cressie goodness-of-fit statistic = 0.0047; and (b) spherical model, nugget effect 0.21, no. components = 1, sill = 0.085, and modified Cressie goodness-of-fit statistic = 0.0012.

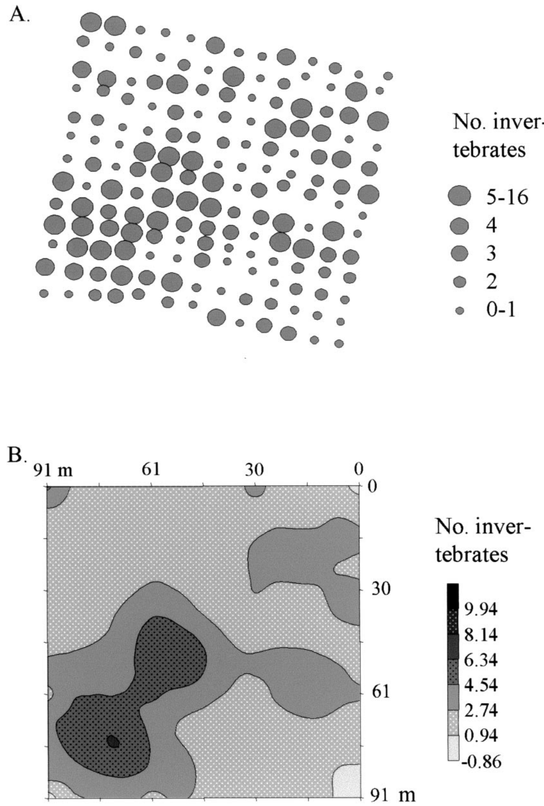

Fig. 2. Comparison of (A) a point map of the actual counts of soil invertebrates and (B) a contour map of kriged estimates of soil invertebrates, Grove Hill, AL, 1997. This example shows how well clusters of invertebrates can be detected in the contour map, whereas it is not easy to detect them in the point map. Numbers on scales are back-transformed from log values.

tively correlated ($P \leq 0.0001$) with masked chafers ($R^2 = 0.46$), *Polyphylla* spp. ($R^2 = 0.40$), and all white grubs ($R^2 = 0.50$), and were negatively correlated with ground beetles ($R^2 = (0.47)$; *Polyphylla* spp. were positively correlated ($P \leq 0.0001$) with *Phyllophaga* spp. ($R^2 = 0.52$), and wireworms were positively correlated ($P \leq 0.0001$) with billbugs ($R^2 = 0.44$).

There were no correlations ($P > 0.05$) between kriged estimates of sound pulse rates and invertebrates in Grove Hill in 1998. Kriged estimates of earthworms were positively correlated with kriged estimates of *Polyphylla* grubs ($R^2 = 0.47$, $P < 0.0001$).

Discussion

Only one invertebrate variable was distributed randomly in Grove Hill in 1997, and no invertebrate variables were distributed randomly in Auburn in 1997. Although there were several invertebrate variables distributed randomly in Grove Hill in 1998, overall the findings were consistent with the theory that insects and other soil invertebrates are rarely randomly distributed (Southwood 1978).

Although sound pulse rate was not significantly correlated with any soil invertebrate at Grove Hill, sound pulse rate did predict the foci of soil invertebrate infestations at Auburn. The different results at the two locations may be due to differences in the density and type of soil invertebrates, or to differences in variables such as soil type, soil composition, soil compaction, or soil moisture. The majority of invertebrates collected in Auburn were green June beetle grubs, which are very mobile, loud insects. Mankin et al. (2000) point out that a major limitation in the present usage of a microphone for detecting insects in the field is the uncertainty in the interpretation of the signals detected by the microphone. The uncertainty may be due to background noise, variability of sound transmission at different recording sites, temporal and environmental variability of insect behavioral activity, and lack of experience in integrating acoustic data with other kinds of information about insects and other organisms at a particular recording site. Due to variability in environmental characteristics, such as soil moisture and compaction, the microphone may have been detecting sounds in a range much farther

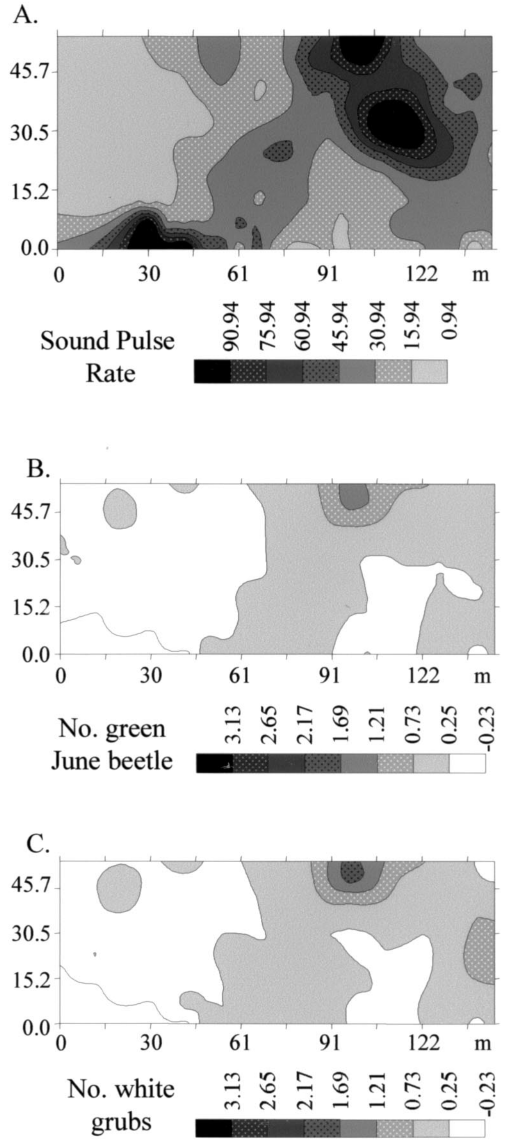

Fig. 3. Distribution of (A) sound pulse rates, (B) green June beetles, and (C) all white grubs (green June beetles and masked chafers) in a perennial grass hayfield in Auburn, AL, in 1997, showing clusters of similar density. These maps are produced from kriged estimates, based on semivariogram models. Numbers on scales are back-transformed from log values.

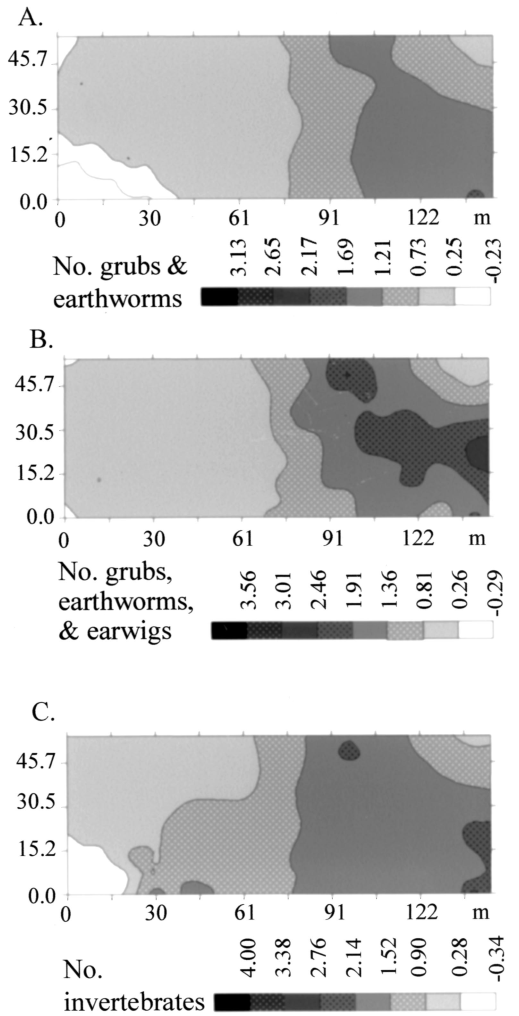

Fig. 4. Distribution of (A) white grubs and earthworms; (B) white grubs, earthworms, and earwigs; and (C) total invertebrates in a perennial grass hayfield in Auburn, AL, in 1997, showing clusters of similar densities. These maps are produced from kriged estimates, based on semivariogram models. Numbers of scales are back-transformed from log values.

than the area being sampled by extraction. The microphone may be able to detect sounds up to 50 cm, which is well beyond the size of the extracted sample (Mankin et al. 2000).

The results of this study indicate that geostatistical techniques and geographic information systems are helpful tools for mapping subterranean insect populations, and that acoustic systems have potential as nondestructive and cost-efficient detection instruments. However, lack of experience with analysis of acoustic data under different field conditions hampered interpretation of the sound pulse data. The large quantity of acoustic data collected in this study will facilitate the identification of signal features other than sound pulse rate that may be important for locating foci of soil insect infestations in the field. Continued studies under a variety of field conditions are needed to train acoustic systems to distinguish insect sounds from background noise with greater reliability outside the laboratory.

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