Practical Use of Spatial Analysis in Precision Targeting for Integrated Pest Management

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Entomologists find themselves in the central position of safeguarding food, fiber, and human health from arthropod pests and their associated pathogens. Unfortunately, the materials we use to control these pests often place us in the precarious position of achieving these honorable goals by apparently risking human health and environmental quality through exposure to toxic compounds. Since the publication of Rachael Carson’s Silent Spring 30 years ago, the adverse effects from pesticides have come under increasing scrutiny.

Improvements to public health through an affordable food supply are due, in part, to pesticides (Anonymous 1993a). However, the public may perceive pesticide use as “risky,” due to adverse effects on environmental quality and human health (Anonymous 1995a). For example, the level of pesticide contamination of groundwater beneath 65% of agricultural land in the European Union exceeds local standards for drinking water (Matteson 1995). Research with yeast cell cultures suggests that some pesticides may function as estrogen mimics and, in combination, their effects may be many times more potent than the effects of a single pesticide (Arnold et al. 1996). In 1993, the National Academy of Sciences (NAS) raised concerns about implications of pesticide residues to children (Anonymous 1993a). A survey of pesticide use in U.S. homes and gardens concluded that pesticides are applied in kitchens, bathrooms, and living spaces in up to 30 million households (36%), and outdoor application of pesticides occurs in 12 million households (Whitmore et al. 1992). Thus, it is not surprising that the NAS report recommended that exposure from all sources—not just agricultural applications—must be considered in assessing risks from pesticides in the diet. Despite reassurance from the American Academy of Pediatrics, that risks from pesticide residues in the diet are “remote, long-term, and theoretical” (Anonymous 1995b), these emotional issues have galvanized the public against use of toxicants as the principal intervention for insect control.

Several recent initiatives have the goal of reducing pesticide use, primarily through an integrated pest management (IPM) approach with less reliance on traditional pesticides. Legislative mandates in parts of the European Union target 50% reductions in pesticide use by the year 2000 (Matteson 1995). The U.S. Department of Agriculture (USDA) announced an initiative in 1993 to bring 75% of U.S. agriculture acreage under some degree of IPM by the year 2000. The Environmental Protection Agency (EPA), in cooperation with the USDA and Food and Drug Administration, inaugurated the “Pesticide Environmental Stewardship Program” in 1994, to foster voluntary reduction in pesticide use with the public and private sectors. In 1995, the Department of Defense signed a Memorandum of Agreement with the EPA to work toward reducing pesticide use, and the Department of Defense set internal goals of a 50% reduction by the year 2000 and a commitment to IPM for all pest management programs.

Definitions of IPM are varied but generally have a common theme of using a variety of management tools, including traditional toxicants, in an integrated approach to managing pest populations. Interventions should be of a least-toxic nature, incorporating, wherever possible, modification of habitat to preclude infestation, and biological, genetic, cultural, or mechanical control measures. A common characteristic of IPM programs is a shift in the
use of resources from materials to labor as applications of interventions change from a calendar basis to an “as needed” basis. As a result, monitoring becomes a dominant and crucial activity (Anonymous 1992, 1993b).

Herein lies one difficulty in implementing IPM practices. Determining presence and distribution of pests requires a higher level of training and skill than is required for calendar-based pesticide applications. Monitoring schemes and inspections typically focus on when and where pests are expected to be found, based on the known biology and behavior of the target organism. Even with the best inspectors, pests in unexpected microhabitats are unlikely to be found. Consequently, because the level of skill varies among inspectors, a consistent, high level of performance is difficult to achieve over time and among locations.

It is likely that pesticides will continue to play a major role in achieving the levels of pest management necessary to ensure public safety from disease vectors and to meet consumer expectations on food quality. This especially is true in domestic and peri-domestic (urban) environments where the public’s pest tolerance thresholds are low (Robinson 1996), or in commercial food establishments where regulatory inspections are stringent. However, in both agricultural and nonagricultural settings, common practice of sustainable IPM programs that meet mandates of less pesticide use, will require simple functional procedures that are compatible with varying levels of skill among practitioners to allow a high level of customized service.

Our experience over the past several years suggests that spatial statistical methods provide that necessary framework, so that interventions can be applied precisely and minimally. This paper will describe simple spatial statistical concepts for developing a precision targeting process that defines pest distribution with minimal a priori knowledge of the behavior of the pest and, more importantly, provides practitioners with simple, documentable procedures for reducing pesticide use. Our case studies, primarily with cockroaches as the target insect, illustrate the use of precision targeting in the urban environment to define discrete areas where interventions are warranted and procedures to quantify subsequent efficacy of these interventions. All described procedures were done with a combination of two commercially available spatial statistical software packages: SURFER for Windows (ver. 6.04, Golden Software, Golden, CO), and VARIOWIN (ver. 2.2, Springer, New York).

Concepts of Spatial Statistics

Spatial statistical analysis, also known as geostatistics, is a powerful tool developed for mineral exploration to determine the size and value of subsurface deposits based on sampling from the surface. The procedures are designed to characterize and model the spatial relationships from sample data, and then use the model to estimate values between sample observations, so that the entire mineral deposit can be quantified. In earth sciences, spatial statistics were founded on the general premise that a certain amount of spatial continuity exists (i.e., observations taken close to each other likely are more similar than observations that are far apart). Readers should consult Isaaks and Srivastava (1989) or Cressie (1993) for full discussions and Pannatier (1996) for summarized procedures on geostatistics.

Fortunately, biological phenomena also exhibit general tendencies of spatial continuity; applications of spatial statistics to ecology have increased in recent years (Chelelmi et al. 1988, Legendre and Fortin 1989, Rossi et al. 1992, Liebhold et al. 1993), with entomological applications in large scale arenas for research on the gypsy moth, *Lymantria dispar* (L.) (Gage et al. 1990, Hohn et al. 1993, Gribko et al. 1995, Liebhold et al. 1995), in gypsy moth IPM projects (Roberts et al. 1993), and on rangeland acridids (Kemp et al. 1989, Johnson 1989). Field-scale studies have used spatial statistics to describe distributions of *Lygus hesperus* Knight in lentils (Schotzko and O’Keeffe 1989, 1990); movement patterns of the Russian wheat aphid, *Diuraphis noxia* (Mordvilko) (Schotzko and Smith 1991, Schotzko and Knudsen 1992); and distribution and movement of the pink bollworm,*Pectinophora gossypiella* (Saunders) in cotton fields (Borth and Huber 1987). For the purpose of this paper, a short synopsis of spatial statistics will suffice.

Unlike the traditional procedures commonly used in biological studies, in which mean-variance relationships are evaluated from observations assumed to be random and independent, spatial statistical procedures recognize that sample observations may be dependent, and nonrandom sampling strategies may be more useful (Schotzko and O’Keeffe 1990). Consequently, spatial analysis measures the extent of dependence in the sample data by evaluating variance as a function of the distance and direction between observations.
As an example, consider the high degree of spatial continuity characterized by an intact vein of gold ore (Fig. 1A). Imagine that a survey team is analyzing samples taken at each node of the grid defined in the figure by the x and y positional coordinates, and is comparing the value at each node with all others in a pairwise manner. Assay values at adjacent nodes will be remarkably similar, regardless of position within the grid; high values will be associated with adjacent high values, and low values will be associated with adjacent low values. However, observations farther apart may be quite different, depending on the distance and direction of separation. This relationship of variability in assay values, as a function of distance separating observation pairs, is shown in Fig. 1B, and illustrates that observation pairs close to each other have lower variance than those pairs separated by greater distances. Therefore, there is great predictability in describing distributions of phenomena that exhibit strong spatial continuity, and this gold deposit can be characterized confidently with a reasonable number of samples.

In contrast, consider an identical vein of gold that was ravaged over geologic time by glaciers and re-buried as a random scatter of nuggets (Fig. 1C). There is no spatial continuity with these gold deposits, and the survey team will find highly variable assay values in pairwise comparisons, whether samples are adjacent or widely separated (Fig. 1D). In this scenario, there is little predictability to be derived from limited samples; characterizing the extent of these gold deposits will require an enormous number of samples.

As one might conclude from this example, a great deal of spatial statistical analysis is devoted to variography—the characterization and mathematical modeling of spatial continuity from sample data sets. Procedurally, each observation, with its location identified by positional coordinates, is paired with every other observation. Pairs are then sorted by the distance (lag) separating them. The square of the difference between observations is summed over all pairs similarly separated, and a variogram (also referred to as a semivariogram) is constructed by plotting half the variance against the lag spacing (e.g., Fig. 1B and D). Typically, at least 30 sample pairs are needed at each lag distance to characterize variance adequately. Other more robust measures of spatial continuity include the standardized variogram, the covariance, and the correlogram. These include special mathematical terms that correct for differences in local means and/or lag variances throughout the sampled area, and typically provide better measurement of spatial continuity (Rossi et al. 1992).

The shape of a suitably-characterized spatial continuity profile (e.g., variogram, covariance) is described by three parameters (Fig. 2). The first of these, coined by mining engineers, is the nugget (y-intercept), or variance associated with the sampling measurement error and/or microscale variance that cannot be measured by the spacing of the sampling.
The shape of the variogram is determined by specific values of the Y-intercept, or nugget (4), sill (24), and range (80). The nugget is the variance associated with the sampling measurement error and/or microscale variance; the sill is the plateau of the profile (variance of the sample observations); and the range is the distance (lag spacing) at which the sill is reached. Variograms are prepared by computer programs that pair every observation with every other observation, then sort and compute the average variance of all data pairs separated by a common distance.

Figure 2. A typical variogram describing the relationship of variance (Yhl) as a function of absolute distance (Ihl) separating observation pairs. The shape of the variogram is defined by specific values of the Y-intercept, or nugget (4), sill (24), and range (80). The nugget is the variance associated with the sampling measurement error and/or microscale variance; the sill is the plateau of the profile (variance of the sample observations); and the range is the distance (lag spacing) at which the sill is reached. Variograms are prepared by computer programs that pair every observation with every other observation, then sort and compute the average variance of all data pairs separated by a common distance.

A number of estimation procedures are available, but the most robust of these is a process called kriging, named for Danie Krige who first developed these interpolative algorithms in the early 1950s. Kriging produces a grid of estimated values that can be used to quantify the entire distribution of the parameter of interest. Finally, kriged data is used to create isolines of equal parameter density visualized as a 2-dimensional contour map or as a 3-dimensional surface plot. This entire process of spatial analysis provides a method of determining the value of the asset (minerals), or in our case, the scope of the problem (insect pest).

IPM Spatial Continuity and the Relative Importance of an Empty Trap

In any pest management plan, the likelihood of success will be greatest if interventions are directed when and where the probability of encountering the pest is high. A corollary would imply that we can minimize collateral effects (e.g., environmental contamination) if we avoid applying interventions where the likelihood of encountering the pest is low. Consequently, it is as important to know where a pest is located as it is to know where it is not located. This sets the stage for spatially-based "precision targeting."

In reality, most pest problems are highly spatial in character at some definable scale. Changes in population distributions may be obvious on a continental scale (e.g., imported fire ants, Solenopsis spp.), but also can be significant even within relatively small spatial areas defined by woods, a riverine system, an agricultural crop, or the walls and features of a building. This situation is illustrated with an example in which the distribution of German cockroaches, Blattella germanica (L.), was assessed at the Chief Petty Officer's Club at the Naval Air Station, Jacksonville, FL.

Although we may be tempted to place sticky traps only in areas where one would anticipate suitable harborage (e.g., kitchen), more information is gained when traps also are distributed in more open areas. This ensures that the entire ecological diversity of a structure is represented in the sampling. For this building of over 1,300 m², 167 sticky traps were used. Fig. 3A is a SURFER map depicting the location of traps superimposed on a "boundary" file showing the location of walls and features of the building. Boundary files are created by listing the x and y coordinates for sequential points that define the building foundation and room boundaries. Similarly, additional items, such as stoves, ovens, refrigerators, and counters can be defined. Coordinates can be determined in any unit of measure from blue prints, simple hand sketches (if proportionally accurate), and bitmap or other computer generated images. These should be converted to meters for practical interpretation. Boundary files and sample coordinates must be in the same units.
Fig. 3. Trapping scheme and variography on German cockroach data associated with the Chief Petty Officer's Club, Naval Air Station, Jacksonville, FL (1993). Panels show locations of 167 sticky traps (dots) (a) used to assess German cockroach distribution; variogram of data from 22 September trap totals (b), also showing number of data pairs for each lag spacing; covariance function of the same data (c); and three kriging algorithms fit to the covariance representing an exponential model with nugget (d), an exponential model without nugget (e), and the linear function without nugget (f). The latter is the default setting in SURFER. Models, with indicative goodness of fit, were created in VARIOWIN. Thin horizontal line is overall data variance.

Spatial analysis was conducted using VARIOWIN program modules that created a "pair comparison file" for calculating and plotting the various measures of spatial continuity. The resultant variogram indicated that observations far apart were more similar than observations close together (Fig. 3B). This is contrary to the concept of spatial continuity, and further variography was undertaken. With this data set, the covariance function (Fig. 3C) best described the strong spatial continuity, characterized by lower variability at smaller lag spacings. Observations 1.3 m apart were less variable than observations 3 m apart, and the variance of data pairs separated by >6 m was at or above the overall data variance (Fig. 3C, horizontal line). In entomological terms, traps about 1.3 m apart were measuring similar population levels. Therefore, cockroach counts in any given trap location could be used to estimate activity for about a 1.3 m radius; but were less reliable at predicting population levels 3 m away, and were of little value in estimating populations >6 m away. This relatively small "nugget effect" suggests that this high trap density provided the maximum resolution of spatial continuity and that there were strong regional differences in population density over the 1,300 m² area. In practical terms, the data show that cockroach densities were heavy in some portions of the building (e.g., the kitchen) and absent elsewhere (e.g., office, hallway, dining room, etc.), and counts in traps separated by <6 m were strongly correlated.

Spatial continuity profiles will reflect artifacts caused by samples having been taken inside a structure. Referring to Fig. 3A, several samples that appear contiguous are either separated by a structural feature of the building (e.g., a wall), or are separated vertically (e.g., a trap placed on the floor and a second trap placed on the counter top above). From a practical standpoint, this sampling scheme is essential for cockroaches. These insects are foragers that are likely to forage vertically and horizontally. However, the 2-dimensional spatial analysis software will interpret only the 2-dimensional distance between these points, which will appear to be nearly contiguous. Depending on data density and lag spacing, this likely will influence the variogram.

This influence of the building's structural features can be handled in three ways. First,
software for interpolating (kriging); 3-dimensional data is available but is not appropriate unless the distribution of a "pest" is truly continuous in 3 dimensions, such as air pollutants. This is not appropriate for cockroaches and most other pests. Second, trap data can be kriged separately for distinct planes such as floor level, counter top level, and wall cabinet level. Data from each room also could be kriged separately to eliminate the effect of a wall on adjacent samples. However, this may not be entomologically reasonable because these pests (and others) often infest walls or use utility chases as conduits between rooms. Third, we can place traps at multiple levels, as is ecologically appropriate for the pest, but collapse all levels and grid data in two dimensions only. Population distribution then can be interpreted by the practitioner in the context of the structural features present. This is the most practical solution, even though traps with very similar 2-dimensional coordinates may have profoundly different insect counts (e.g., high counts on the floor but low counts on top of the wall cabinet directly above trap on floor). Recognizing this, we can compensate in part by selecting a kriging algorithm that strongly "honors" the observations, and by selecting a fine grid spacing (see below).

If spatially-based precision targeting is to be used by the general pest management practitioner, it must be reasonably simple to conduct and geostatistically "forgiving" (e.g., does not require rigorous statistical variography). Therefore, we conducted a simple study with one cockroach data set to compare contour maps of estimated distributions produced with three distinctly different kriging models. We used VARIOWIN for constructing the mathematical models describing the covariance function of spatial continuity (Fig. 3 D–F). Two exponential models were developed, with one having the y-intercept (nugget) forced to zero. The third model was a simple linear equation also with a zero intercept. Subsequently, these models were used with SURFER’s kriging program for a 120 x 120 grid spacing to produce contour maps (Fig. 4).

Although the exponential algorithm with a y-intercept (nugget) of 11.7 provided the best mathematical fit (smallest indicative goodness of fit), it produces the greatest variability in residuals of the estimates (estimated vs. observed trap catch) (Fig. 4A). This is attributed
to a nonzero nugget, which fails to honor the original data observations (maximum trap catch of 28), and functions as a smoothing interpolator rather than an exact interpolator (zero nugget). In the context of entomological science, a zero nugget indicating strong confidence in trap counts (measurement error = 0) may be broadly warranted for estimating population foci, as is the purpose in precision targeting for pest management. The effect of a linear versus an exponential kriging algorithm with zero nugget was assessed by mathematically subtracting the value at each grid node estimated with the linear model from the value at the corresponding grid node estimated with the exponential model. This procedure was done using SURFER grid/math options. Resultant contours (Fig. 4D) reveal that the maximum difference was only 0.3 cockroaches in areas of infestation. Furthermore, this zero-nugget exponential algorithm produced high estimates where traps and pests were non-existent (extrapolations; coordinate [45,58]) or under sampled (interpolations; coordinate [62,50]).

We have concluded that SURFER's default settings of a linear kriging algorithm with zero nugget is adequate and satisfactorily defines foci when used with a spatial distribution of samples similar to those described herein. It must be stressed, however, that in any spatial analysis, accuracy is highly dependent on the number and distribution of samples within the area of interest, especially when a zero nugget is used.

Kriging with a zero nugget (exact interpolator) provides additional utility when spatial distributions are normalized to define and quantify areas that exceed given numeric or action thresholds (Isaaks and Srivastava 1989; Liebholt et al. 1991, 1993; Rossi et al. 1992). This process, called “indicator kriging,” provides the basis for precision targeting, risk assessment, and spatial assessment of efficacy for interventions (Brenner 1993, Brenner et al. 1998). Because spatial analysis estimates an entire distribution based on values and spatial distribution of the samples, it is assumed that the distribution, for example, of 75% of the sampled population reflects the distribution of 75% of the entire population. To conduct indicator kriging, a spreadsheet is used to sort trap counts in descending order (Table 1). In adjacent columns, cumulative totals and cumulative proportions (cumulative frequency distributions) are calculated. In a third column, the indicator “score” of 1 is assigned for each trap count whose value exceeds a given threshold (i.e., “indicator threshold”); all other observations receive a score of zero. The threshold, tailored to the specific requirements of the pest management goal, can be determined either as a maximum tolerable insect count (e.g., a “trap threshold” that indicates an economic or aesthetic injury level), as a population proportion that must be suppressed (e.g., for a disease vector, a population density may need to be reduced by 90% to drop below transmission thresholds), or as a particular decile of the cumulative frequency distribution (Rossi et al. 1992, Liebholt et al. 1993, Brenner 1993).

Because overall population or activity levels will vary among dates, as measured by trap counts, population proportions and trap thresholds selected for determining indicator scores also will vary. When assigning indica-

### Table 1. Sample from spreadsheet showing creation of indicator scores describing distribution for 80.7% of population, reflecting a trap threshold of 14.

<table>
<thead>
<tr>
<th>Trap ID</th>
<th>x Coord.</th>
<th>y Coord.</th>
<th>Count</th>
<th>Cumulative Total</th>
<th>Cumulative frequency distribution</th>
<th>Indicator Score</th>
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<td>0.06</td>
<td>32</td>
<td>32</td>
<td>0.177</td>
<td>1</td>
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<td>63</td>
<td>0.348</td>
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<td>4.56</td>
<td>1.20</td>
<td>29</td>
<td>92</td>
<td>0.508</td>
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<td>90</td>
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Columns are sorted by “count” in descending order. See text for explanation on assigning scores by cumulative frequency distribution (cfd) and count. For each row, the cfd is calculated by dividing the cumulative total by 181.
tor scores, all traps with the same number of insects must be included in the same indicator category. To illustrate this, assume for the moment that you have a pest population, and a reduction of 75% is your goal. Referring to Table 1, the target population proportion is 0.75, and that particular cumulative frequency distribution is obtained approximately (0.729) with the first of two traps each containing 14 insects. Then, either both traps must receive indicator scores of 1, resulting in a higher cumulative frequency distribution (in this case 0.807), or both traps must receive scores of zero, and the trap threshold becomes >14 insects with its associated lower cumulative frequency distribution (e.g., 0.652). Based on these trap data then, you would target either 65.2% or 80.7% of the population. Let us assume that 80.7% is selected; therefore, all traps capturing 14 or more insects (e.g., the indicator threshold) account for 0.807 of the population.

If the “indicator” column of zeros and ones is now used as input for kriging, the resultant gridded data will consist of numbers between zero and one. These numbers reflect the estimated probability, at each grid node, that a trap placed at that location would capture 14 or more insects (i.e., probability of exceeding threshold value used to define the indicator score). The resultant contour map provides “probability contours” defining the spatial distribution for 80.7% of the entire estimated population.

**Basics of the Precision Targeting Process: Chief Petty Officer’s Club**

Populations were sampled at weekly intervals from 1 to 22 September 1993. Because trap locations were consistent among trap dates, this approach provided sensitivity to changes in spatial population patterns. Numbers varied among sample dates (Fig. 5), but foci continued to be identified principally in the kitchen (coordinates [43-55, 40-50]) and pantry areas (coordinates [37-44, 47-54]). Variability in population distribution among these sample dates likely was due to several factors. Human activity was high with meals served daily and social functions that occurred frequently. Restocking and/or redistribution of pantry items could have impacted harboring cockroaches. Variety in menu items and normal variability in cleaning practices also could have resulted in redistribution of food resources. Previous studies conducted in our ARS experimental structures clearly showed that German cockroach populations dramatically redistributed within five days as food and water resources were redistributed (Brenner 1993).

Probability contours that cumulatively define the location of ~85% of the cockroach population for each sample date are shown in Fig. 5E-H. Contour display has been restricted to reveal only those areas with probability ≥ 0.5 of contributing toward this cumulative population level. We selected this number arbitrarily because we really are not interested in the areas where the probability is <0.5 that it contributes to the target cumulative population level. These maps provide insight into the dynamics of the population. For example, the two foci in Fig. 5E at coordinates [52,38] and [53,43] are detected on all sampling dates, indicating a high degree of habitat stability. Other foci exhibit a higher degree of variability (i.e., instability) both temporally and spatially, but definition of areas consistently harboring cockroaches is clearly evident. Fig. 5H also shows two newer foci at coordinates [54,41] and [54,48]. These were associated with some ongoing repair to the plumbing and wallboard, apparently providing additional suitable microhabitats. This illustrates a strong advantage precision targeting provides to IPM—the ability to detect populations in unexpected areas. Even a well-trained inspector, who had visited this site previously, would tend primarily to inspect only those areas where his previous experience had indicated that problems existed. With precision targeting, the spatial analysis, unbiased by previous experience, determines the distribution. Consequently, spatial distributions can be determined consistently, regardless of the skill level of the technician.

Both direction and relative degree of change in distribution can be visualized by mathematically subtracting the probabilities of exceeding a threshold on one date from probabilities of exceeding the same threshold on another date. This is accomplished using the “grid/math” option in SURFER to subtract the grids that were obtained by kriging the indicators. Figure 6 depicts the resultant “spatial dynamics indices” (Brenner 1993), with possible values ranging from +1 to −1, comparing 1 and 22 September populations. Blue contours reflect areas of emigrations (population decreases between sample dates), and red contours show areas of immigration (population increases between sample dates). Zero contours (gray) show areas of no change between the two dates (stability). All trap locations exceeding the...
indicator threshold trap value on 22 September are posted with either green or black dots. Black dots identify locations that were high on both dates (high habitat stability), and necessarily are associated with zero contour lines (no change). Other areas depicting no changes that are not associated with data postings were below the threshold for both dates. The spatial dynamics indices are useful for identifying areas with persistent infestations, characterized graphically by zero contour areas at locations exceeding thresholds. The indices may provide insight into the salient behavioral traits of the pest and the microhabitat characteristics that foster population stability. For IPM, these are the locations that may require additional attention and may be suitable for alternatives to toxicants (e.g., exclusionary devices).

The 22 September probability contour map (Fig. 5H) was used as the precision targeting guide to test a prototype vacuum device for removing cockroaches and their attendant allergen. The process required approximately 45 minutes. The device uses dry heat rather than a chemical irritant to flush cockroaches from their harborsages (Brenner et al. 1996, patent pending) and may have strong utility for IPM programs in schools, health care facilities, and similar situations. Fig. 5H defines the distribution of 86% of the population, reflected by the distribution of all traps capturing seven or
more cockroaches. The focus at coordinates [52,38] was avoided purposely to provide a nonintervened point of comparison. The remaining foci were targeted for treatment with the prototype vacuum device.

Contours resulting from postvacuuming trap counts (Fig. 7A) illustrated that two of the targeted foci remained, and that several additional traps collected 1-3 cockroaches. The same trap threshold (tt) used to construct the precision targeting map (tt = 7) was used to construct the postintervention (comparative) probability contours (Fig. 7B). This clearly showed the focus that had been avoided purposely, and (embarrassingly) defined one focus that had been missed at coordinates [53,45]. Herein lies another powerful advantage of precision targeting. Whereas traditional statistics would provide only a measure of percentage population reduction, the comparative probability contour provides the documentation as to where the intervention failed and possibly provides insight as to why. Careful inspection of Fig. 5E reveals that this population at coordinate [53,45] coincides with a 10 x 10 cm x 5 m electrical service box 1.5 m above the floor containing six electrical receptacles. In Fig. 5G, it appears that a second population is centered on the front half of the food preparation counter (contiguous to the electrical service box) that contained a small integral storage refrigerator. Both foci appear in Fig. 5H as an oblong focus. We failed to vacuum the area near the storage refrigerator. Although precision targeting did not eliminate our "incompetence," it did document it and provided immediate feedback useful in correcting our error. Subsequent management efforts would begin a phase of customized "mop up" operations (see further example below). Because coordinates are in units of measure (m), we also can quantify the area in which population levels were reduced below our threshold. Preintervention regions defining our target totaled 47.8 m², whereas remaining postintervention foci totaled only 1.9 m².

**Precision Targeting to Enhancing Level of Service and Reduce Pesticide Use: U.S.S. Canopus**

In the days preceding the decommissioning of the U.S.S. Canopus, a submarine tender, we demonstrated the use of precision targeting in a reduced pesticide management strategy. Baits replaced crack and crevice sprays, and monitoring replaced calendar-based treatments. Constraints on time and access to the ship limited our research to one of several adjacent galleys characterized by stainless steel equipment crammed into a 55 m² area. The German cockroach population was monitored with 27 sticky traps placed overnight (Fig. 8A). We used the default kriging options to estimate population density at 13 cm intervals (35 x 50 grid).

Spatial distribution based on trap counts (Fig. 8B) and the associated probability contours (Fig. 8C) revealed six major foci accounting for 81% of the cumulative frequency distribution. This example demonstrates that spatial analysis has an additional utility; the planar (horizontal) area bounded by the contours can be calculated. These data can be used to illustrate how precision targeting, even while using traditional toxicants, can be used.
Fig. 7. Cockroach distribution after vacuuming showing estimated numbers of cockroaches (a) and the postintervention comparative contours (b) based on the preintervention threshold of seven cockroaches per trap. Compare areas within contours of panel b with those of Fig. 5H.

to quantify reduction in pesticide use. Fig. 9 compares the areas likely to be treated with a pesticide with and without the use of precision targeting. Standard pest management procedures would have consisted of a thorough crack and crevice treatment with a residual toxicant. The upper panel of Fig. 9 was prepared by using SURFER’s digitize command to define the arbitrary boundary of areas where a crack and crevice treatment might be (values of 1) and would not be (values of 0) applied.

These arbitrary “treatment” points were kriged, and contours were plotted as bands of potential application. In reality, these are probabilities ≥0.5 of surface treatment, depending on the “rigor” at which the treatment might be applied. SURFER calculates the cumulative horizontal area bound by the various contours. For example, a practitioner treating areas of the galley defined by values from 0.5 through 1.0 would have treated 15.3 m² of the horizontal surface area. Treating the galley more judiciously, defined by values 0.9 through 1.0, would total only 4.6 m². Even if the same toxicant were selected, precision targeting could reduce the amount of pesticide delivered by defining the areas based on the likelihood of encountering pest foci, rather than the characteristics of potential harborage sites. Treating the precision targeted areas bounded by values of 0.7–1.0 constitutes a 70% reduction in area treated with pesticide from the...
Fig. 8. Spatial analyses conducted on German cockroach populations aboard the U.S.S. Canopus (July 1994). Panels show (a) distribution of 27 sample locations (sticky traps) at various levels (floor, counter, and other) in one galley; (b) initial distribution of German cockroaches, expressed as a contour map of numbers per trap; (c) the probability contours (i.e., "precision targeting" map) delineating population foci for 81% of the population, reflecting a trap threshold of 13; (d) contours describing distribution 24-hr posttreatment; (e) resultant postintervention comparative contours (compare to panel c); (f) new precision targeting map describing distribution for 76% of survivors (trap threshold of three); (g) 2-wk postinterventional contour map showing numbers per trap; and (h) postintervention comparative contours based on trap threshold of three (compare to panel f). For each panel, boundary file delineates galley equipment. It, trap threshold; cfd, cumulative frequency distribution used to determine It. See Table 1 for example of creating indicator scores for probability contours.

We chose to treat the galley with an experimental hydrodynamic gel bait (injectable with a syringe) containing 0.5% chlorpyrifos designed to function especially well in areas where microclimates are harsh or fluctuate broadly (Brenner and Burns 1997, patent pending). Comparison of population levels (Fig. 8D) and probability contours at 24 h posttreatment revealed that five of the six foci constitut-

standard crack and crevice treatment. Treating only areas bound by values 0.9 - 1.0 reflects a 95% reduction (4.6 vs. 0.2 m²) in area treated with pesticide. Note that this illustration is oversimplified; a residual spray is unlikely to be applied, as the precision targeting map implies, to open areas between foci. However, this research illustrates how spatial analysis can be applied to agricultural pests where current procedures commonly result in the treatment of an entire field once economic injury thresholds have been exceeded. Nestel and Klein (1995) suggest that spatial analysis may be useful to restrict, both spatially and temporally, the application of growth regulators for managing leafhopper populations in deciduous orchards.
Fig. 9. Illustration on use of precision targeting and probability contours in determining areas likely to be treated. Top half represents areas where a pest management practitioner would likely apply a crack and crevice treatment. Lower half is precision targeting map delineating probable distribution for 81% of population. Color scale reflects potential treatment zones, and numbers within color scale are probability contour labels. Numbers above and below color scale are areas (m²) defined by contours ≥ color zone for nonprecision targeting strategy (above) and with precision targeting strategy (below). See text for details of preparation.

ing 81% of the population were reduced below the indicator trap threshold of 13 (Fig. 8C vs. 8E). Although 24 h is an insufficient interval to measure the full impact of a bait, these data were used to elevate the level of control further by defining the population distribution for 76% of those cockroaches that had survived (Fig. 8F). This reduced the trap threshold value to three, and a secondary focus at coordinates [4.5, 5.5] was revealed. Consequently, bait was reapplied to these areas. In total, we used 53 g of bait applied to 0.013 m² of surface area, a 99.7% reduction compared to the traditional crack and crevice residual spray.
At two weeks posttreatment, only two traps caught more than two cockroaches (Fig. 8G). The final probability contour map indicates that the limited continuing problems were restricted to a part of the galley that was adjacent to a larger, untreated galley (Fig. 8H). It is at these locations that we recommended that monitoring should be routinely performed with just a few traps. Under a proposed precision targeting IPM program, the full complement of 27 traps would be deployed upon any positive trap catches, and a prescriptive treatment would be applied according to the spatial analysis. In summary, this precision targeting approach on the Canopus resulted in a 90% population reduction in two weeks, a 99.7% reduction in area of treated surfaces, and a shift in emphasis to monitor with a few traps placed strategically according to the final probability contour map.

**Detecting Stage-Related Spatial Patterns: Asian Cockroaches**

The immature stages of many insects behave differently than the adults. This is obvious in holometabolous insects such as mosquitoes and butterflies but may be more subtle in hemimetabolous or paurometabolous species. Spatial analysis provides the sensitivity to detect subtle differences, as was shown by Schotzko and O'Keefe (1989) for Lygus hesperus Knight. In the case of the Asian cockroach, Blattella asahinai Mizukubo, these differences have implications for management.

We tested whether a treatment barrier (0.5% chlorpyrifos pelletized bait) extending at least 30 m from apartment buildings, would preclude the nightly incursion of adult Asian cockroaches that are strong fliers and attracted to brightly lit areas of a building (Fig. 10). Spatial assessment had been conducted previously to demonstrate that nymphal stages infest leaf litter and thatch in lawns (Brenner et al. 1988). Counts of nymphs and adults from 100 traps were kriged separately. Pretreatment data (Fig. 11A) revealed heavy nymphal populations in the adjacent wooded area characterized by heavy vegetative undergrowth and some adults near the apartment buildings. The 1 d posttreatment data (Fig. 11B) confirmed that, during application, we had exhausted the supply of the bait near coordinates [130,55]. By 10 d posttreatment, nymphs and adults were virtually nonexistent near the buildings (Fig. 11C). At six-weeks posttreatment (Fig. 11D), nymphal populations had not reinfested the treated area in any appreciable manner, but adult distribution indicated three foci near the buildings—all associated with areas brightened at night by security lighting. Therefore, despite the effectiveness of the bait at reducing nymphal populations near the structure, the likelihood of reinfestation by gravid females was greatest adjacent to the buildings where likelihood of human encounter was high.

This spatial assessment suggested that an IPM plan for this species should include a component to reduce attraction of adult insects to lighting near buildings. An option would be to use sodium vapor lamps for security lighting and yellow incandescent bulbs for porch lighting, both of which are less attractive to adults. The information derived from this spatial analysis also provided a strategic insight that

**Fig. 10.** Schematic diagram of test site for managing Asian cockroaches near Tampa, FL (July, August 1987).
monitoring near light sources could detect the incipient stages of infestation by gravid females, and would allow managers to proactively preclude the large nymphal populations of the successive generation before they become established (Brenner 1991).

**Spatial Analysis in a Zero-threshold, Biocide-Sensitive Area: Caribbean Fruit Fly Mass Rearing Facilities**

The Florida Department of Agriculture, Division of Plant Industries, operates a mass-rearing facility for managing the Caribbean fruit fly, *Anastrepha suspensa* (Loew), using the sterile insect technique. Over 20 million flies are reared weekly in this 975 m$^2$ facility maintained at 27°C and 80% relative humidity. It is an ideal environment for any of several species of peridomestic cockroaches that may gain entrance from outdoor habitats. Risks associated with cockroach infestations include potential contamination of fruit fly-rearing stock with microbial associates of the cockroaches (Brenner et al. 1987) and the potentially disastrous effects of using a pesticide in an insect rearing facility. Consequently, acceptable thresholds of infestation are low (zero), and nontoxic interventions are a priority. Circumstances at this facility, pertaining to risks, are what might be expected in health care facilities, nursing homes, or other biologically-sensitive areas.

Initial inspection of the facilities revealed a stark environment (relative to harboring opportunities for cockroaches) consisting of uncluttered laboratories, and rearing rooms without cabinets, counters, or laboratory casework. Under normal operations, the large overhead door (Fig. 12, shown as a gap at coordinates [30,7]) was kept open while larval-rearing media was mixed from materials stored in the same room. Over 18 months, we used jar traps or sticky traps baited with dry distiller's grain (Brenner and Patterson 1989) on five sampling dates at 62 locations, including several on the building perimeter. In the initial trapping (Fig. 12A), separate spatial analysis of nymphs and adults for the Australian cockroach, *Periplaneta australasiae* (F), indicated only two foci of immatures (coordinates [18,7] and [12.5,10], contours not shown separately by stage) and a more expansive distribution of adults elsewhere. Subsequent inspection near the [18,7] focus of immatures revealed access holes in hollow metal tubing of wheeled transport racks used to move rearing trays to the various rooms. Over the ensuing few months, these were filled with an expansive polyurethane foam; postmodification sampling verified complete absence of cockroaches from these racks (Fig. 12 B and C). Inspection of three foci associated with doorways (coordinates [27.5,17], [27,19], and [38,17]) revealed door frames with rust holes resulting from the humid environment. Other areas...
identified as sporadic foci by the spatial analysis included floor drains with hollow under-sides protected from the copious amounts of water used daily and a free-standing incubator (coordinates [17,21]). Doors and frames were scheduled for replacement with stainless steel units, but budgetary constraints precluded immediate action. By 1 July 1993, it was apparent that periodic trapping would not reduce populations sufficiently (Fig. 12D); facility managers agreed to allow a small quantity of our 0.5% chlorpyrifos bait in 29.5 mL souffle cups to be placed according to the precision targeting map from 9 pm until 6 am. After five consecutive nights, the facility was resampled, and only four cockroaches were trapped inside (Fig. 12E). Routine monitoring over the past three years typically produced 0-3 cockroaches in traps proximal to the diet mixing area [25-35, 10-12]. In this example, a precision targeting strategy facilitated an integrated approach characterized by monitoring for low or incipient infestation levels, modification of habitat to preclude infestation, and judicious use of a toxic bait that provided acceptable management.

Utility of Minimal Measurement for Detecting Trends: Fumigation of Stored-Products

Despite our desire to take samples in sufficient numbers for rigorous spatial assessment, there are circumstances in which only a few samples are possible. Spatial representation still provides information more useful than a simple reporting of mean and standard error. As an example, we present a case study of insect-infested seed grain. Seed grain often is stored in bins for various periods of time until it can be processed and bagged. During this time, insect pests present a serious threat, especially in the southeastern states. Therefore, grain often is fumigated immediately after it is placed in storage and again whenever serious infestation becomes evident.

During summer 1996, a field study was conducted on oats, stored at a seed-processing plant near Williston, FL, to test a new version of the automatic insect counter described by Shuman et al. (1996). The counter was incorporated into polyethylene grain probe traps (Barak et al. 1990), with the slant of the holes...
reversed (Subramanyam et al. 1989), and counted insects as they fell through an infrared beam. The usefulness of such a device in monitoring stored-product insects could be further enhanced if continuously repeated counts could be transmitted directly to a computer for posting to a map of the trap layout. These then could be used immediately to generate contour maps of insect distribution. Changes in numbers and distribution of insect pests could be viewed in real time from a secure, remote location and used to make management decisions. Automated counting would make pest monitoring a far more practical undertaking than it is at present. Although grain probe and other pitfall traps have long been available to storage managers, their use has been limited by the time required for servicing and data processing as well as the need for repeated entry into confined spaces.

The oats stored at Williston had been harvested in May and held under cover in field carts at the processing plant until they were placed in a steel storage bin on 25 June. They were fumigated on 27 June by placing calcium phosphide tablets on the surface of the grain and in the aeration duct, which was then sealed. By 17 July, the phosphine level had fallen below 0.1 ppm, and eight traps were placed just below the grain surface (Fig. 13). It is apparent from the figures that 12 traps would have provided a more uniform coverage of the 24 m² surface, but current configuration of the counting system limited the number of traps to eight. In addition to the automatic counts, insects were removed from the traps and counted at weekly intervals. By 12 September, the insect population had reached such a high level that a second fumigation became necessary. Traps were removed on that date, and fumigation was performed on 15 September. On 19 September, the phosphine level was still 3.0 ppm, but, by 24 September, it had declined to 0.07 ppm, and the traps were replaced.

Spatial analysis of trap data (manual counts) collected before and after the second fumigation permitted assessment of treatment efficacy and provided documentation of the results. The first sample, taken during the fourth week following initial fumigation, showed a mean (± SE) trap catch of 9.9 (± 1.3) adult insects, mostly foreign grain beetles, *Ahasverus advena* (Waltl); corn sap beetles, *Carpophilus dimidiatus* (F.); and hairy fungus beetles, *Typhaea stercorae* (L.). These were well distributed over the grain surface with a maximum in the east sector of the bin and a minimum in the southwest sector (Fig. 13A). By the eleventh week, the mean number of insects captured had increased to 121.8 (±
13.9) (Fig. 13B). In addition to A. avena and T. sternocera, these included sawtoothed grain beetles, Oryzaephilus surinamensis (L.), flat grain beetles, Cryptolestes pusillus (Schönher), rusty grain beetles, Cryptolestes ferrugineus (Stephens), red flour beetles, Tribolium castaneum (Herbst), and a species of Corticaria (Lathridiidae). Several hundred psocids also were captured, but these were of little concern to the plant manager and are not included in the present counts. The insect population was concentrated near the bin wall from east through north to west and declined toward the center and southwest (Fig. 13B). Following the second fumigation, mean trap catch fell to 11.4 ± 1.8 and the spatial distribution (Figs. 13C and D), with a maximum in the east and a minimum in the southwest areas, closely resembled the distribution observed after the initial fumigation (Fig. 13A).

For comparison with the manual counts in grain probe traps, the automatic insect counts before and after the second fumigation are illustrated in Fig. 14. The mean number of insects counted during the eleventh week was 334.9 ± 51.8, but included a substantial proportion of psocids. Following the second fumigation, the mean number fell to 52.4 ± 12.3, many of which were again psocids. Comparison of Fig. 13B and 14A (note difference in scale of z-axis) shows that the spatial distribution of the automatic counts was different from that of the manual counts and resulted from the inclusion of psocids in the automatic counts. In general, both counts were highest along the bin wall and lowest at the center, but the manual counts showed a minimum at the southwest whereas the automatic counts showed a maximum. There was, in fact, a negative correlation between numbers of psocids and of all other insects in the manual counts. Although this could have a biological cause, it is probably artifact, resulting from destruction of psocids in the trap by other insects; the degree of destruction would be expected to increase as the number of other insects increased. The population maximum indicated in Fig. 14B is mostly psocids.

Although the second fumigation drastically reduced insect numbers and allowed sufficient time for the oats to be processed before sustaining heavy damage, too many insects survived for it to be considered an unqualified success. The eaves of the bin were closed, but the bin was far from airtight and the method of application did not provide for introduction of the fumigant gas deep within the grain bulk. In fact, the remarkable similarity of insect distribution after the first fumigation to that after the second suggests a heterogeneity of the grain surface with respect to gas penetration that did not change from one fumigation to the next. Areas of low penetrability would provide refuges for insect survival and could account for the similarity. The spatial analysis indicates the need for follow-up treatment and provides the information needed for precision targeting. One alternative would be another fumigation in which the calcium phosphate tablets are probed deeply into the grain mass, concentrating them in the foci of infestation identified by contour analysis. Another alternative would be to initiate a biological control effort.

Biological control holds considerable promise as a means of controlling storage pests (Brower et al. 1995), particularly when it is used as one component of an IPM program. The EPA has exempted parasitic and predatory insects “from the requirement of a tolerance when they are used in accordance with good agricultural and pest control practices to control insect pests of stored raw whole grains such as corn, small grains, rice, soybeans, peanuts, and other legumes either bulk or warehoused in bags” (EPA 1992). These insects also can be used to control pest populations in empty warehouses and in warehouses containing processed packaged products. Parasitic and predatory insects used in stored grain as pesticides are exempt from regulation under the Federal Insecticide, Fungicide, and Rodenticide Act. They also are exempt from the requirement of a tolerance under the Federal Food, Drug, and Cosmetic Act and do not contribute to an evaluation of “infested” by the Federal Grain Inspection Service. They are not exempt, however, from the Food and Drug Administration’s “defect action levels” for insect fragments (i.e., maximum number permissible).

Spatial analysis can play an especially important role in the effective application of biological control to stored product protection by enabling precision targeting of predator and parasitoid releases. The high cost of producing these agents makes this especially important. In the case of our example, natural enemies could have been selectively introduced into the foci of infestation indicated in Fig. 13A and C, after the insect population was brought to a manageable level by fumigation. It may be argued that precision targeting is unnecessary when releasing beneficial insects into storages because their searching capacity is sufficient to locate pockets of infestation regardless of where they are released. However, this has never been demonstrated experimentally, and,
as illustrated by the spatial assessment in the next example, may not be the case.

Potential Targeting of Stored-Product Pest Population Foci in Grain Bins with Biological Control Agents

Successful control of stored-product insects in farm-storages seldom can be achieved today by application of insecticides to the grain because of resistance in most pest populations to many long-used protectants (for example see Haliscak and Beeman 1983). Generally, pesticide resistance ratios (ratio of the LD$_{50}$ for a resistant strain to the LD$_{50}$ for a susceptible strain used as a standard of comparison) are such that only those heterozygous- and homozygous-susceptible individuals present at the time of initial storage are likely to be killed (Muggleton 1986). Pesticide levels degrade rapidly on the surface of grain kernels and residual control probably is limited severely.
(Rowlands 1975). However, several strategies readily are available for use in an IPM program to augment the suppression achieved by grain protectants. Among the most promising is biological control, but there has been little practical investigation of its potential in an IPM program. An unusual approach involves the use of insecticide-resistant parasitoids in combination with an insecticide (Baker and Throne 1995). Examples of insecticide-resistant natural enemies of stored-product insects include a pteromalid parasitoid of larval weevils that feed within the grain kernels (Baker and Weaver 1993), a braconid parasitoid of moth larvae (Baker et al. 1995), and a generalist anthocorid predator of stored product insects (Baker and Arbogast 1995). Organisms like these have the ability to suppress insecticide-resistant pest populations directly. Precision targeting of pest foci should, in theory, result in an enhanced level of suppression by natural enemies by decreasing their searching time, optimizing their reproduction, and assuring a readily available food supply. However, as stated previously, the need for precision targeting has been debated because of the small areas involved and the host-seeking ability of the natural enemy. The example described here shows clearly that precision targeting can provide useful information.

Corn was stored on 26 August 1993 in a steel bin 5.5 m (diam.) by 4.9 m high on a farm in Bamberg Co., SC. This is the farm from which resistant parasitoids described in Baker and Weaver (1993) were collected. Insect populations were monitored starting 1 September by counting weekly captures in 28 polyethylene probe traps placed just beneath the surface of the grain and left in place for one week. Traps were evenly distributed around the center of the bin; four at a distance of 0.45 m from the center, eight at 1.35 m, and sixteen at 2.25 m. Therefore, the area sampled by each trap, on average, was effectively less than one m² of grain surface. A treatment with a malathion spray was applied to the corn as it was augured into the bin. Initial levels of approximately 12 ppm (Arbogast, unpublished data) were in excess of the recommended label rate. Residues degraded rapidly to approximately 5 ppm by the fifth week of storage (Arbogast, unpublished data). Fig. 15A shows a spatial distribution of the total insect population, excluding biological control organisms. The dominant species were the red flour beetle, hairy fungus beetle, flat grain beetle, and nitidulids. There also were low numbers of the maize weevil, Sitophilus zeamais Motschulsky (Weaver, unpublished data). Fig. 15B shows the foci of natural enemies present at the same time. These included generalist predators (e.g., Xylocoris spp.) in the greatest numbers, and pteromalid parasitoids and staphylinid predators of the beetles (Weaver, unpublished data). All contours were generated with linear kriging (zero nugget) of a 75 x 75 grid.

Spatial assessment clearly illustrates a fundamental problem with the assumption that innate host-seeking will result in a rapidly developing predator-prey interaction at the pest focus in a storage bin. The pest population was concentrated in the center of the bin where the finer particles tend to accumulate during bin loading (Fig. 15A). The focus of endemic natural enemies was centered at the south bin wall (Fig. 15B). Contours for the natural enemies showed little overlap with those for the pest foci (Fig. 15A and B). A suitable environment for establishment of a reproductive population of natural enemies may have been found at the first search site randomly chosen, and subsequent dispersal through an environment contaminated with toxic residue may have been reduced greatly. Thus, it is not apparent that an augmentative, but undirected,
release of natural enemies will locate a focus when hosts or prey are available at most search points. Rather, it appears from these data that effective biocontrol can result only from release of generalist and specialist organisms directly at the pest foci as soon as possible during growth of the pest population. It is clear from this example that a likely location of pests will be in the centrally located, small particle, dockage material that is difficult to fumigate—this is a good location to precision target. However, we recommend that a monitoring program that is intermediate in intensity between that illustrated in this example and the previous case study be used. Such a sampling strategy would be adequate to pinpoint any location that needs an augmentative release of natural enemies. Multiple species of insecticide-resistant natural enemies could then be targeted to control the pest community that exists at such foci in stored grain.

Conclusion

It is likely that spatial ecologists will conclude that we have oversimplified spatial statistical analysis by our acceptance of default settings of linear kriging with zero nugget. Our objectives, however, are to develop a simplified, functional use of spatial analysis that facilitates the use of IPM strategies to reduce pesticide use. The techniques we have described in these examples provide an objective determination of population distributions that are relatively independent of differing skill level of technicians and provide continuity of observations over time. This approach strengthens application of IPM. Indicator kriging and its associated probability contours provide a tool that can be used in assigning risks and in comparing treatment options. Spatial dynamics indices provide documentation and comparative assessments of changes in insect distributions resulting from IPM interventions.

The precision targeting concept is the infrastructure for our project to develop standardized IPM procedures that will allow the Department of Defense to reduce pesticide use and pollution. Because pest management in the Department of Defense increasingly is being outsourced to the private sector, the procedures we develop also must meet private sector demands for efficacy and efficiency. Although the circumstances that define pest distribution in any particular application (especially inside a building) will be dynamic across time and space, we contend that variography cannot be incorporated in a simplified, standardized procedure. In our experience, variography is a powerful research tool for elucidating spatial behavioral characteristics of insect species. It will continue to be instrumental in developing standardized monitoring tools for common pests. We contend that the dynamics of pest distributions across time and space can best be assessed through many inexpensively obtained observations in a systematic sampling scheme (to ensure adequate spatial coverage) with supplemental observations where ecological profiles change abruptly. Much of our research efforts, therefore, will focus on developing affordable sampling devices and methods for enhanced monitoring.

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References Cited


Richard J. Brenner and Dana A. Focks are research leader, and research entomologist, respectively, in the Imported Fire Ant and House- hold Insects Research Unit. Currently, they are using the processes described here for spatially-based risk assessment and mitigation of medically-important insects in cooperative projects with Department of Defense, EPA, FDA, NASA, and Centers for Disease Control and Prevention. Richard T. Arbogast, Dennis Shuman, and David K. Weaver are research entomologist, research electrical engineer, and research associate entomologist, respectively, in the Postharvest and Bioregulation Research Unit. Their research is focusing on proactive detection and monitoring systems for stored-product insects, integrating pheromone-based monitors, electronic monitoring, and spatial analysis. Currently, David Weaver is research assistant professor at the Department of Entomology, Montana State University, in Bozeman, MT.
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