PREPARING FOR THE 21ST CENTURY: RESEARCH METHODS IN DEVELOPING MANAGEMENT STRATEGIES FOR ARTHROPODS AND ALLERGENS IN THE STRUCTURAL ENVIRONMENT

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Abstract—Public pressures, and mandates by government agencies will require that we develop strategies that reduce exposure of humans to pesticides. These must be developed so that they manipulate populations to the extent that likelihood of infestation is reduced, or assuming that they will infest a structure, likelihood of survival is reduced. Development of such strategies requires experimental 'monitored' natural environments and novel statistical procedures that evaluate spatial relationships. In pursuance of these goals, research was initiated to develop spatial analysis techniques to quantify the response of German cockroaches to a redistribution of food and water resources. A population from a Miami housing project was released into a specially-constructed, climate-controlled, monitored 'natural' structure. Spatial distributions were measured repeatedly from Aug. 1990 through January 1991. Spatial analysis procedures were developed (based on geostatistics) to measure distribution before and after food and water resources were redistributed in mid-November. Probability contours and a "spatial dynamics index" were developed to detect and quantify spatial continuity and to examine the strength of those changes. Data comparing tap counts for 2 dates were used to evaluate statistical procedures. Although traditional statistics failed to show a difference in these populations, spatial statistics clearly revealed that changes had occurred due to resource redistribution. Probability contours, based on indicator data sets, have strong value at locating foci. These can be used as a guide in a management program for prescribing treatment, or for allocating and partitioning resources based on probabilities of reinfestation. Probability contours and spatial dynamics indices may have wide-spread commercial utility in several areas: prescribing treatment, or allocating and partitioning resources based on probabilities of reinfestation, documenting effective pest management, assessment of interventions in housedust mite abatement, confirmation of residue reduction (dirt, grease, duct debris, etc.), or confirmation of foci reduction. In Gainesville, spatial dynamics indices are being used in developing strategies using non-traditional chemical interventions (repellents), non-chemical interventions (enhanced air flow, construction design, moisture management, etc.), and allergen management. In preparation of expanding research in this area, 3 additional buildings have been constructed; one of which was constructed without exterior walls, so that experimental materials or procedures can be evaluated as a management strategy for the next century.

INTRODUCTION

Because our laboratory is federal, our research mission mandates that we anticipate the needs of the public and the industry into the next century, and develop improved strategies for safeguarding human health and possessions from arthropod pests. Clearly, a major concern is a reduction in exposure to pesticides, resulting from public pressures, and the regulatory actions of government agencies. This, combined with the costs of pesticide development and registration, and requisite liability protection, will radically change pest management in the next century. The industry likely will need to focus on manipulating populations by managing elements of the structural environment (using chemical and non-chemical interventions) to reduce the likelihood that pests will infest our belongings, and to reduce the probability that those gaining access will survive in our environment. Additionally, there will be opportunities to garner a new image of managing the quality of the structural environment by managing the attendant pathogens and allergens of pests.

All infestations in structures are spatial in nature; some areas are conducive to survival and foster population growth, whereas others are not. Arthropod allergens, allergens from pets, and molds are more abundant in certain areas of a structure, and under specific conditions (periods of high humidity with little air flow for molds, periods of low humidity and high air circulation for aerosolizing pet allergens). Understanding the dynamics of infestations and the appropriate measures of management require (1) an awareness of these spatial relationships, (2) knowledge of the factors that influence distribution, and (3) an understanding of how populations respond to changing resources (i.e., manipulation). Research procedures and statistics traditionally used in our industry cannot address these elements fully; new procedures are necessary.

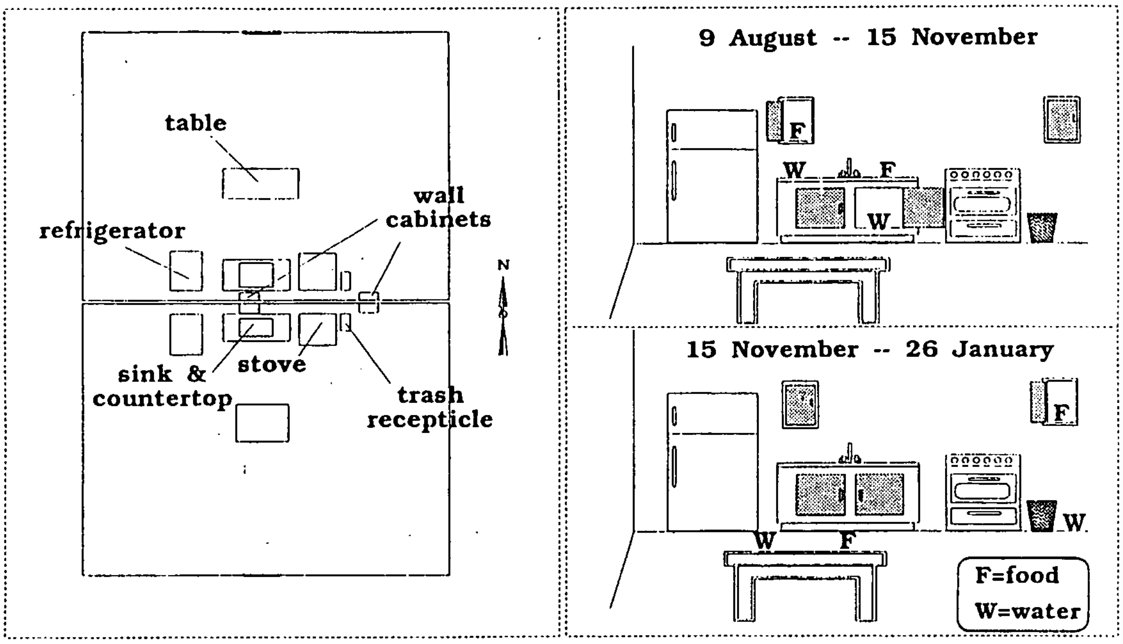


Figure 1. Schematic of 1040 ft.2 research structure (40 x 26 ft.; 12.2 x 8 m) showing positioning of kitchen furnishings (left panel), and illustration of how food and water were redistributed throughout the study.

In pursuance of these goals, we constructed a building for the purpose of infesting it with cockroaches, monitoring the microclimate, cockroach activity, and allergen distribution. The complete details of this project will be published elsewhere in their entirety (Brenner and Rossi, in prep.). This presentation will focus on the development of spatial analysis techniques that have broad applicability to industries associated with pests, sanitation, or environmental quality. The data set used in this paper was generated in a study to quantify the response of German cockroaches, *Blattella germanica* (L.) to a redistribution of food and water resources in a monitored environment. Subsequently, techniques developed in this study were used to develop a.cockroach management program for a Caribbean fruit fly mass-rearing facility.

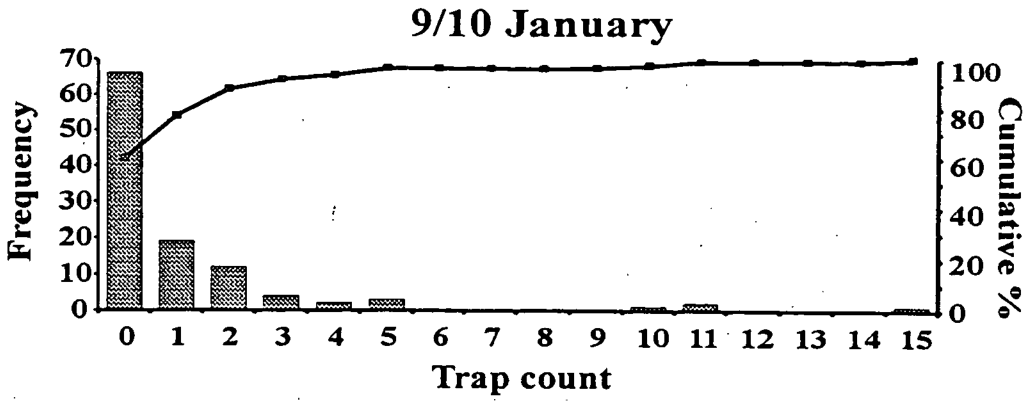
MATERIALS AND METHODS

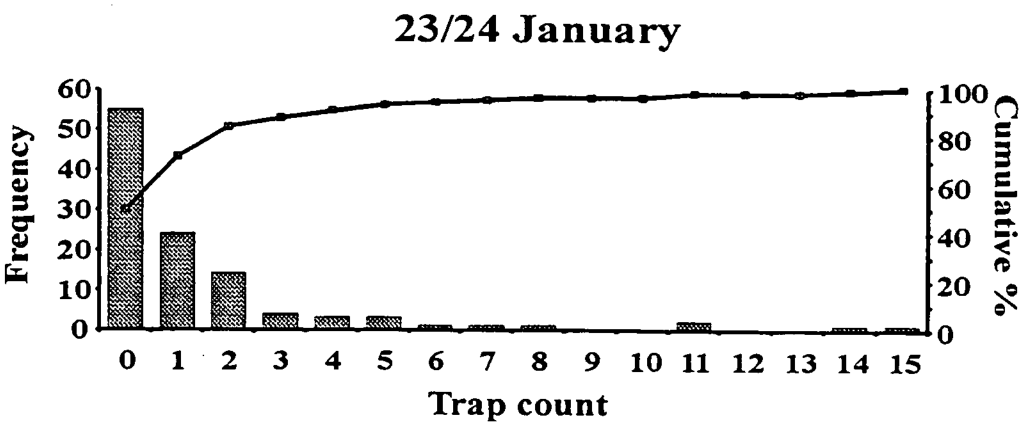
Environment and Resource Distribution

A population of German cockroaches from a Miami housing project was released into a specially-constructed, climate-controlled, monitored 'natural' structure. This consisted of a 12.2 x 8 m building (slab on grade) composed of 2 kitchens (each 6.1 x 8 m) in mirror image. Furnishings for each kitchen included a countertop with sink, a frost-free refrigerator, a 4-burner electric stove, 2 wall cabinets, a waste basket, and a kitchen table (Fig. 1). Food (laboratory rat chow and "Ritz" brand crackers) was placed at 2 locations within each kitchen, and 2 water stations also were positioned within each kitchen (see Fig. 1). On 15 November, food and water resources were redistributed.

Population Sampling

On 9 August 1990, 600 German cockroaches (100 males, 100 females, and 400 nymphs) were released onto the countertop in each kitchen. Spatial distributions were measured repeatedly from Aug. 1990 through January 1991 by placing 55 live traps in each kitchen overnight (1 pt. glass jelly jars with the upper 3 cm greased with a mixture of mineral oil and petroleum jelly [3:2]). Trap locations were numbered and marked with adhesive labels to ensure that subsequent trap placement was repeatable. Traps were baited with bread soaked in beer that was placed in a screened





	9/10 Jan	23/24 Jan
Mean	1.54	1.72
Known Variance	15.26	10.08
Observations	110	110
Hypothesized Mean Difference	0	
z	-0.3788	
P(Z<=z) two-tail	0.35241	NS
z Critical two-tail	1.64485	

Figure 2. Traditional descriptive statistics for 2 sampling periods. Frequency distributions (histograms) and cumulative percentages (line) are similar for these dates. A 'Z' test (bottom panel) confirms the hypothesis that the mean differences between sample counts is not significant. Compare to Figure 3.

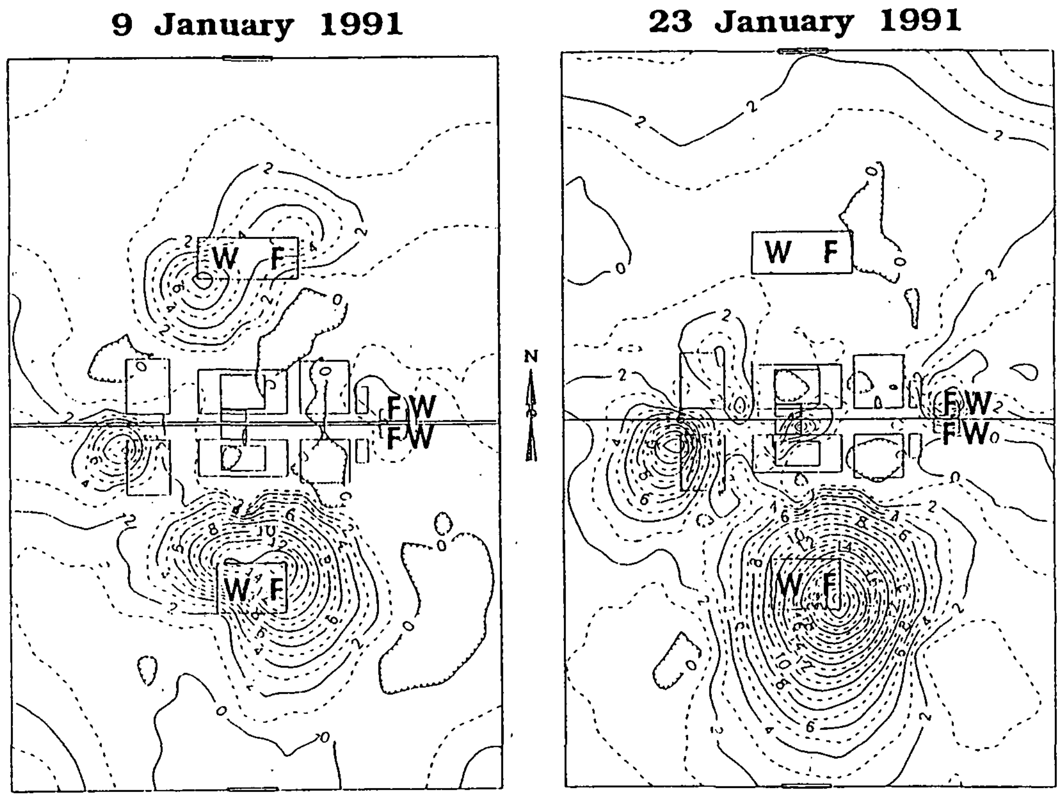


Figure 3. Spatial analysis of the same data analyzed in Figure 2. Contours (min. = 0, intervals of 1) show areas of equal cockroach density, based on numbers per trap per night. In contrast to the analysis of Figure 2, this indicates that a behavioral change has occurred, resulting in different spatial distribution.

condiment cup to preclude ingestion. In each kitchen, traps were distributed on the floor, in and on cabinets, and on top and within appliances; these were arranged in a coarse grid of 16 on the floor (4 x 4) with the remaining 39 distributed in locations of significant ecological diversity (interface of vertical and horizontal elements, corners of surfaces, etc.). In late October, allergen distribution was assessed using cockroach excrement as markers. Video image analysis was used to estimate the volume (mm^3/cm^2 sample area) of excrement adhering to each of 108 samples (7 cm^2 sticky label adpressed to the surface, removed, and inverted for imaging).

Basics of Spatial Analyses

General spatial analysis theory is described by Isaaks & Srivastava (1989) and Rossi *et al.* (1992), and I urge interested readers to consult this readable text. Spatial statistics was developed by mineral engineers to define the distribution of minerals; because it is costly to recover them, knowing their precise subterranean spatial distribution is essential. Unlike traditional statistics that assumes random sampling and independence of observations, spatial statistics recognizes that some spatial continuity may exist, and that samples taken close to each other may yield similar values (strong spatial continuity). In ecological or behavior studies, this is commonly the case; trees tend to occur together, grass tends to occur in patches, asphalt tends to be continuous. In the case of German cockroaches, they tend to aggregate.

Spatial continuity is modeled using variograms (or similar parameters such as madograms, inverse covariance variograms, or correlograms [Isaaks and Srivastava, 1989; Englund and Sparks 1991]) which evaluate the variance of all observations that are separated by a similar distance. With any given data set consisting of values whose sample locations are defined by their X and Y spatial coordinates, spatial statistical procedures pair each observation with every other observation. The distance between each pair is calculated, and pairs are then pooled by their common distances (e.g.,

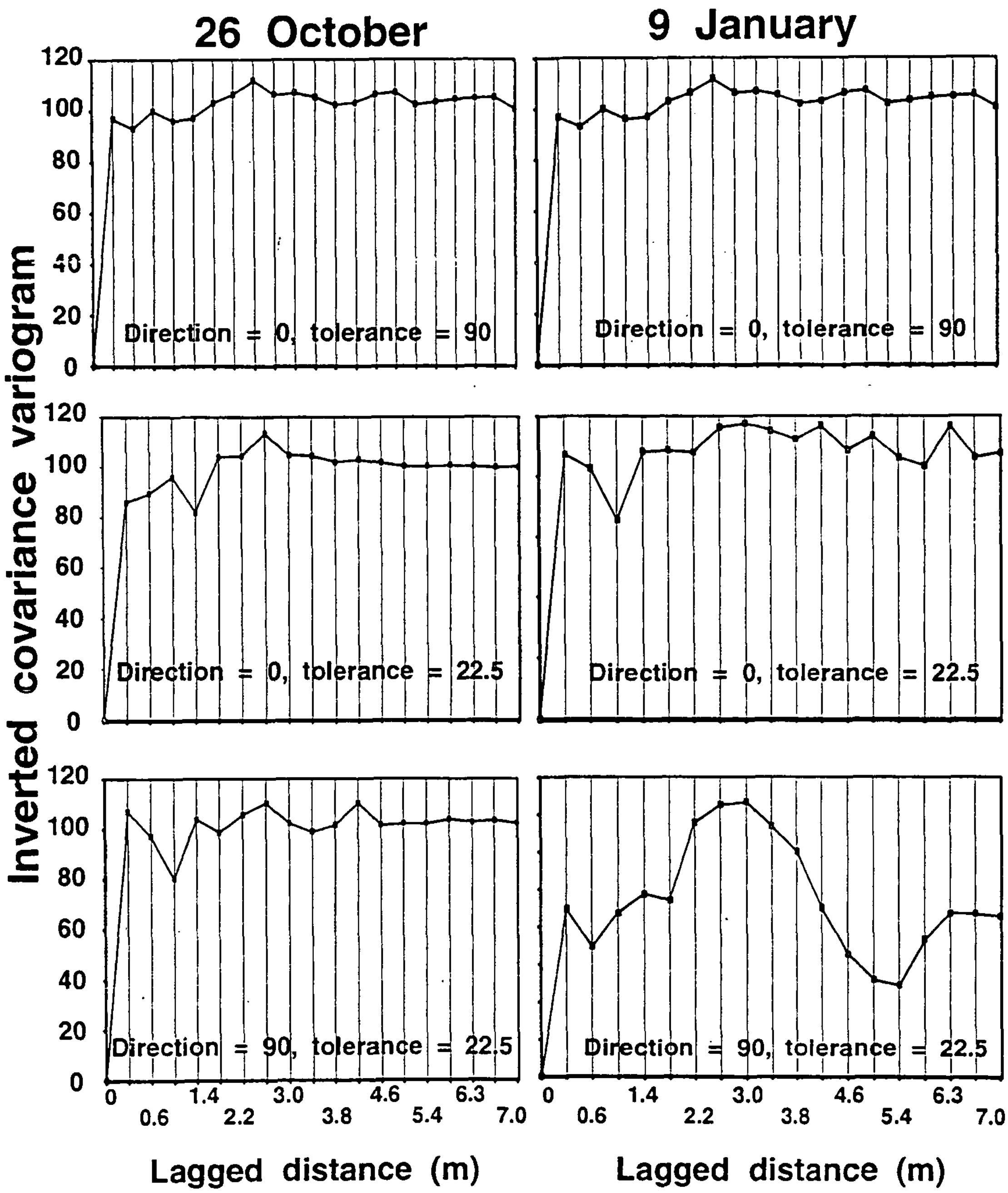


Figure 4. Inverted covariance variograms illustrating omnidirectional (top panels), east-west directional (middle panels), and north-south directional (bottom panels) relationships between traps separated by various distances (lagged distance). For 9 January, there is a marked similarity in trap counts separated by 5-5.4 m on a north-south axis. See text for description.

all pairs of observations separated by 1 m, by 2 m, etc.). For each grouping, or bin, half the variance is plotted (ordinate) against the mean distance separating the pairs (abscissa). Variograms can be omnidirectional --- in which case all pairs, say 2 m apart, are pooled regardless of direction --- or they can be directional --- in which case pairs are formed only for observations where the second location is a given direction (e.g., 90° ± 10°) from the first location. Specific analysis for the German cockroach data included evaluation of omnidirectional and directional variograms using GEO-EAS software (EPA provided) and customized programs written in Turbo Basic.

This relationship of variance by distance is then used to estimate values at unsampled locations using a mathematical technique known as Kriging. For the German cockroach data, populations were estimated at 1 ft intervals (0.304 m) using ordinary Kriging (Surfer, Ver. 4, Golden Graphics, Golden, Colorado). In simple terms, the computer program estimated the number of cockroaches that would be expected at 1 ft. intervals (1040 sites, in this data set). Each estimate is made by examining the relationships of trap counts in all directions at all distances from the point to be estimated. Contour maps are then constructed from these 1040 point estimates.

Probability Contours and Spatial Dynamics Indices

Probability contours were developed that provide the probability (at any location within the structure) of obtaining trap counts above a given threshold. This was accomplished by converting raw trap counts to "indicators". Values at or above a given threshold were replaced with the value 1; all trap counts below the threshold were given values of 0. Subsequently, these indicator data sets were Kriged, and contours were prepared as described above.

A "spatial dynamics index" was developed so that spatial distributions over time could be compared to detect and quantify changes in spatial continuity and to examine the strength of those changes. This was accomplished by Kriging 2 or more indicator data sets for a given threshold. The estimated probability at each of the 1040 points for a given date is subtracted from the estimated probability at the same point on a second date. The resultant value (ranging from -1 to +1) is an expression of emigration (negative value) or immigration (positive value), and the absolute value is the relative strength of the change.

Techniques of spatial analysis were used to develop a cockroach management program at the Caribbean Fruit Fly Rearing Facilities at the Division of Plant Industries, Florida Department of Agriculture, in Gainesville, Florida. Fifty-three traps, baited with dry distiller's grain (Brenner and Patterson, 1989; 1989; 1991), were placed throughout the 10,500 ft^2 facilities (965 m^3) where they remained overnight. From trap counts, contour maps were prepared to determine areas of infestation for treatment and subsequent periodic surveillance trapping.

RESULTS

Descriptive statistics for data collected on 9/10 January, and 23/24 January are presented in Fig. 2. Frequency histograms and cumulative percentages of the 110 observations are remarkably similar for these dates. A 'z' test, performed to assess populations sampled on these dates, failed to show any significant difference in terms of the mean number of cockroaches per trap. From this test, one would conclude that the populations are similar and stable. However, these same data, when viewed from the context of spatial statistics, reveal a distinct shift away from the north kitchen (Fig. 3). Thus, one would conclude that something has occurred that has resulted in a change in behavior of the population.

Figure 4 illustrates that inverted covariance variograms (ICV) can be used to detect shifts in the spatial patterns even before data are Kriged and contour maps are prepared. Omnidirectional IVCs (direction = 0°[east], tolerance = 90°; Fig. 4 top panels) indicate that no particular spatial continuity exists even in observations ca. 0.3 m apart. A directional IVC examining the spatial continuity of observations on an east-west axis (Fig. 4, middle panels) reveals the general phenomenon that observations separated by 1.0-1.4 m are somewhat more similar (i.e., less variable) than observations separated by other distances. However, a directional IVC examining relationships on a north-south axis reveals a major change in spatial continuity (Fig. 4, bottom panels); strong similarity in counts occurs near 0.6 - 1.8 m separation, and stronger similarity at ca. 5.0 - 5.4 m separation.

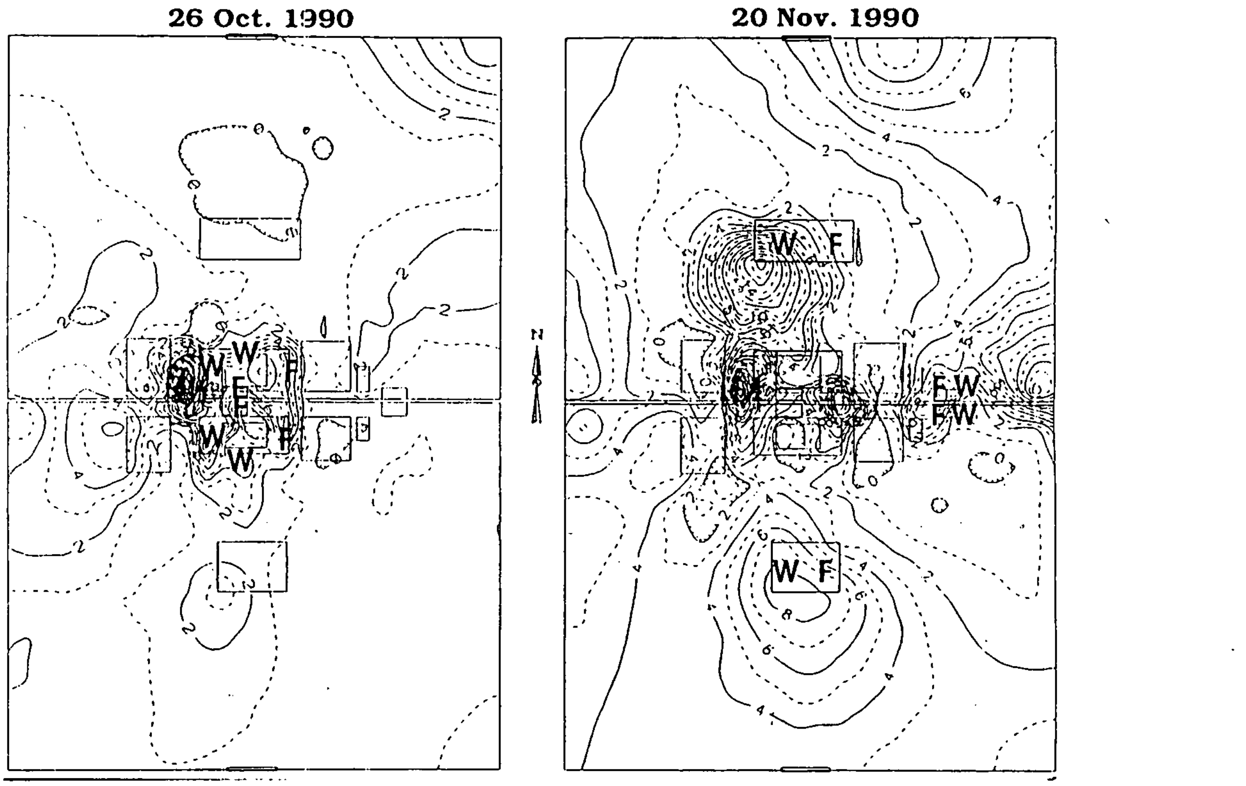


Figure 5. Contour maps showing changes in cockroach distribution following redistribution of food and water resources. Contours (min. = 0, intervals of 1) reflect areas of common cockroach density.

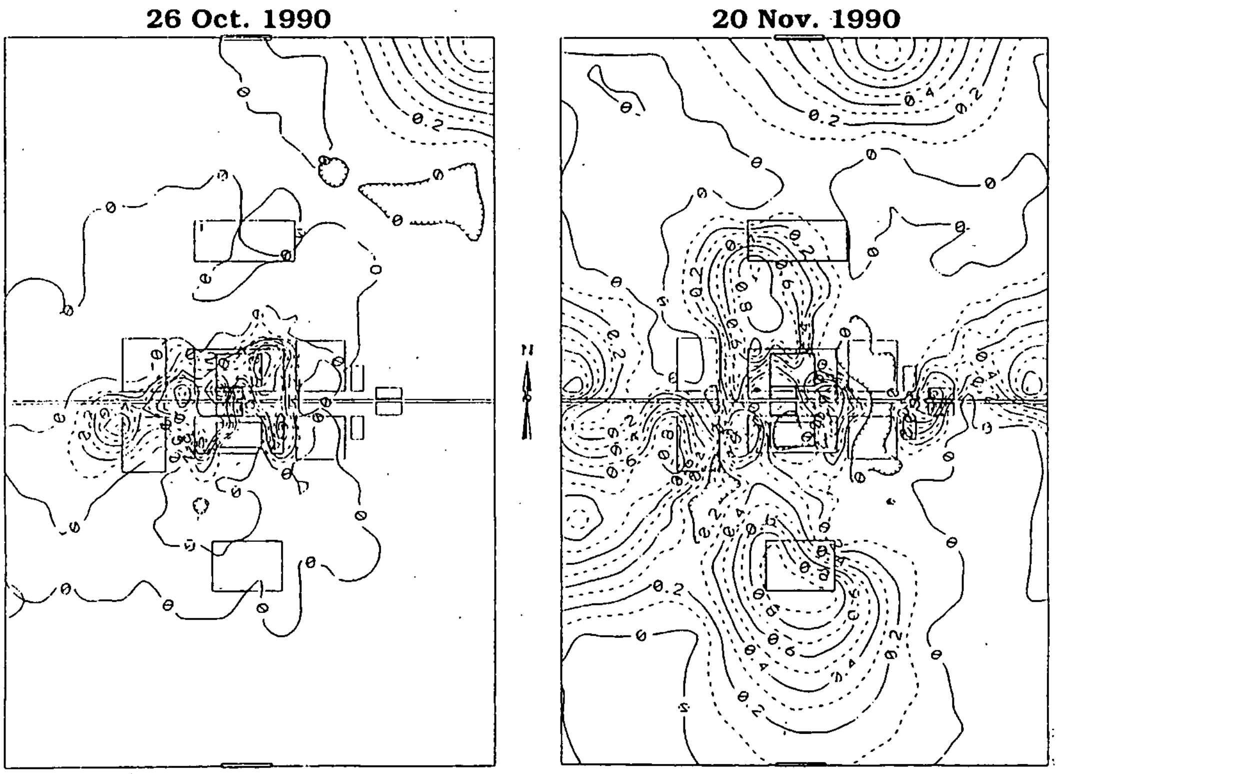


Figure 6. Probability contours (min. = 0, intervals are 0.1) showing probability of obtaining a trap count of 6 or more. This method shows foci, and is largely unbiased by unusually high trap counts. See text for description of preparing probability contours.

The significance of these numbers can be seen in Figs. 3 and 5 (left panels). Cockroach populations on 26 Oct. were concentrated on and near the sink cabinet (Fig. 5), and the similarity of traps with ca. 1 m separation in this area is high (low variance). In contrast, by 9 January (Fig. 3), populations had relocated from the sink cabinet to the kitchen tables. Variance of pairs (on a north-south axis) within 1 m is still quite low (similar values for trap pairs near sink counter [both trap counts low], and on table tops [both trap counts high]). Additionally, the two tables are separated by ca. 5.0-5.4 m on a north-south axis, and because these traps have high counts, similarity is high. Thus, these pairs exhibit low variance (Fig. 4).

Figure 5 shows that cockroach populations redistributed rapidly following the relocation of food and water stations. Contours, expressed in terms of numbers captured in live traps per night, show that foraging patterns had changed markedly. Data also can be expressed in terms of probabilities of obtaining trap counts above a given threshold. Counts of 6 or greater were selected, because this number represented the top 15% of observations. These probability contours (Fig. 6), comprised of values ranging from 0-1, reveal population centers that are unbiased by particularly large counts. In October (Fig. 6, left panel), the likelihood of obtaining trap counts of 6 or more was high only for locations near the sink cabinet, the refrigerator in the south kitchen, and in the NE corner of the north kitchen. However, following the relocation of food and water, population centers also expanded to include the tables, and the east and west walls near the dividing wall.

Data for these two dates were combined to calculate a spatial dynamics index. With values that range from -1 to +1 (Fig. 7), this allows dates to be compared and reveals direction of change (negative values show emigration, positive values connote immigrations) and the degree of change (absolute value). From October to November (following the redistribution of resources) there was general emigration from the sink cabinet toward the tables and walls. Large dots superimposed on these figures show locations of indicator traps (traps with values above the selected threshold) on the latter date of comparison.

Comparison of dates in January clearly reveals an important combination of zero contours and indicator traps on the table in the south kitchen (Fig. 7, right panel). This reveals an area of stasis, suggesting that conditions at these locations are suitable for sustaining populations over time.

Probability contours also were constructed for the distribution of surface allergens, as measured by the distribution of excrement. Samples taken on 26 October revealed that 25% of all excrement was confined largely to two locations (Fig. 8, left panel). However, probability contours for 75% of all excrement encompassed food-preparation areas, and the floor immediately surrounding the sink cabinet.

Figure 9 illustrates the application of spatial statistics in a management program. The contour map of adults (Fig. 9, center panel) revealed foci near doorways at two locations. Subsequent inspection revealed that hollow metal doors were harboring some adults who had gained access through rust holes (these facilities maintain 80-85% RH). However, a contour map of nymphs (Fig. 9, lower panel) indicates a pattern of infestation in rooms near the west wall where vertical racks (tubular steel) on rolling casters were stored. Normal operation of the facilities includes use of these racks to maintain trays of larval flies during the early stages of development. Trays are transferred to large screened cages following pupation. These vertical steel racks are moved to various rooms by inserting a hook and handle into a 1 cm hole in the lower frame. Further inspection revealed that some of these frames had become infested with cockroaches.

DISCUSSION

If we are to reduce exposure of humans to pesticides, strategies must be developed that *manipulate* populations to the extent that likelihood of infestation is reduced, or assuming that they will infest a structure, likelihood of survival is reduced. Assuming pursuance of these goals, there are two major limitations of commonly used research tools in this industry: lack of experimental facilities and inadequate spatial assessments. Because pests and pollutants respond to complexities of the indoor environment, controlled facilities are needed for monitoring environmental parameters. Spatial assessments are necessary to obtain an appropriate perspective of the biotic and abiotic interactions, and to assess the impact of experimental interventions. Data presented here clearly

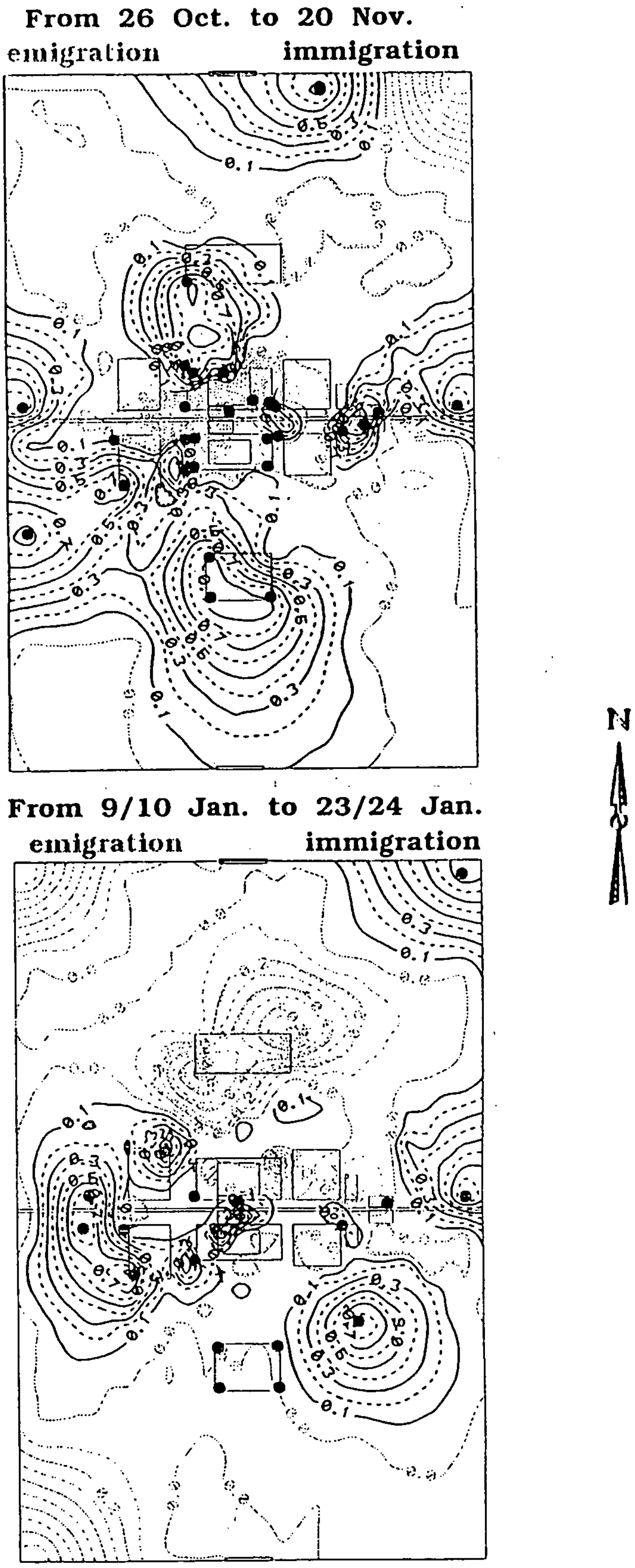


Figure 7. Spatial dynamics indices provide a mechanism to compare spatial distributions on different dates. They reveal areas of emigration (light contours) and areas of immigration (dark contours). Dots represent trap sites on the latter date with counts of 6 or more.

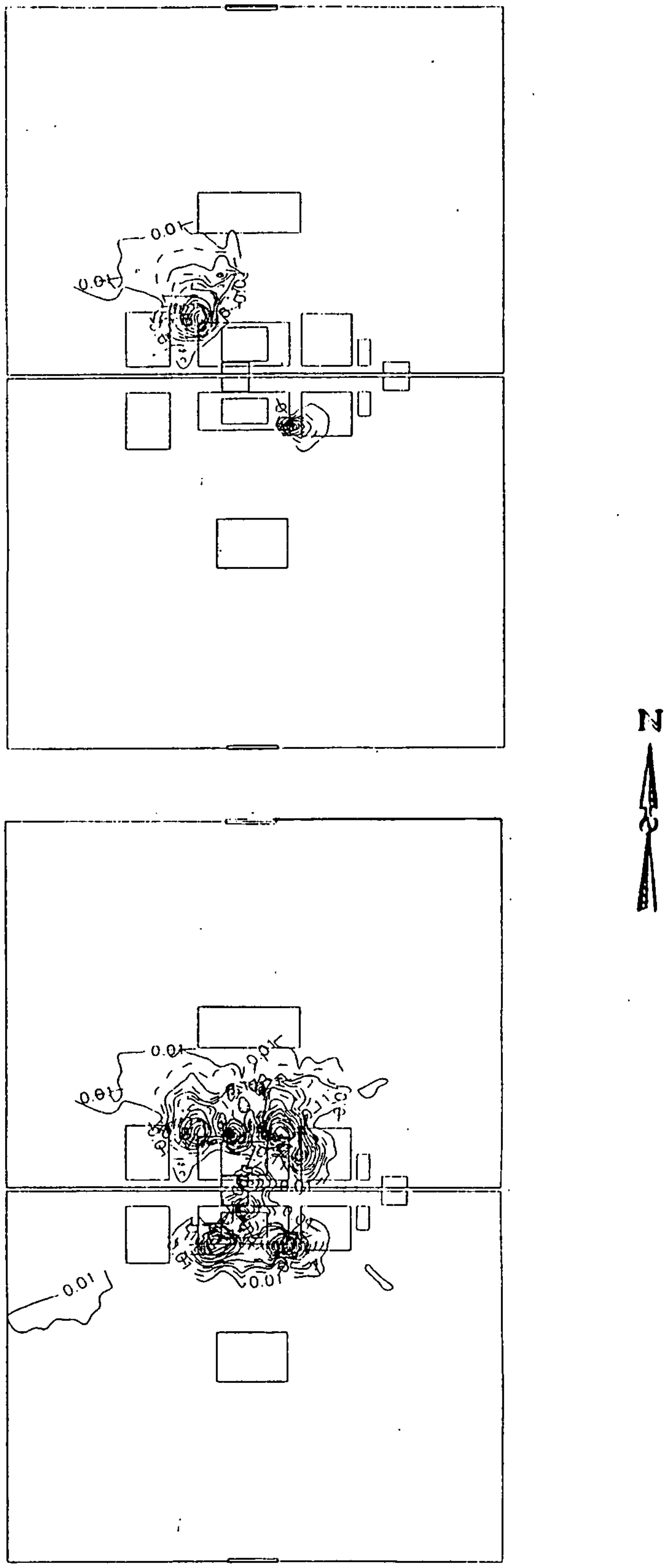


Figure 8. Probability contours (min. = 0.01, intervals of 0.1) for the distribution of surface allergens on 26 October, 1990, based tribution of cockroach excrement. See text for description of sampling and analysis procedures.

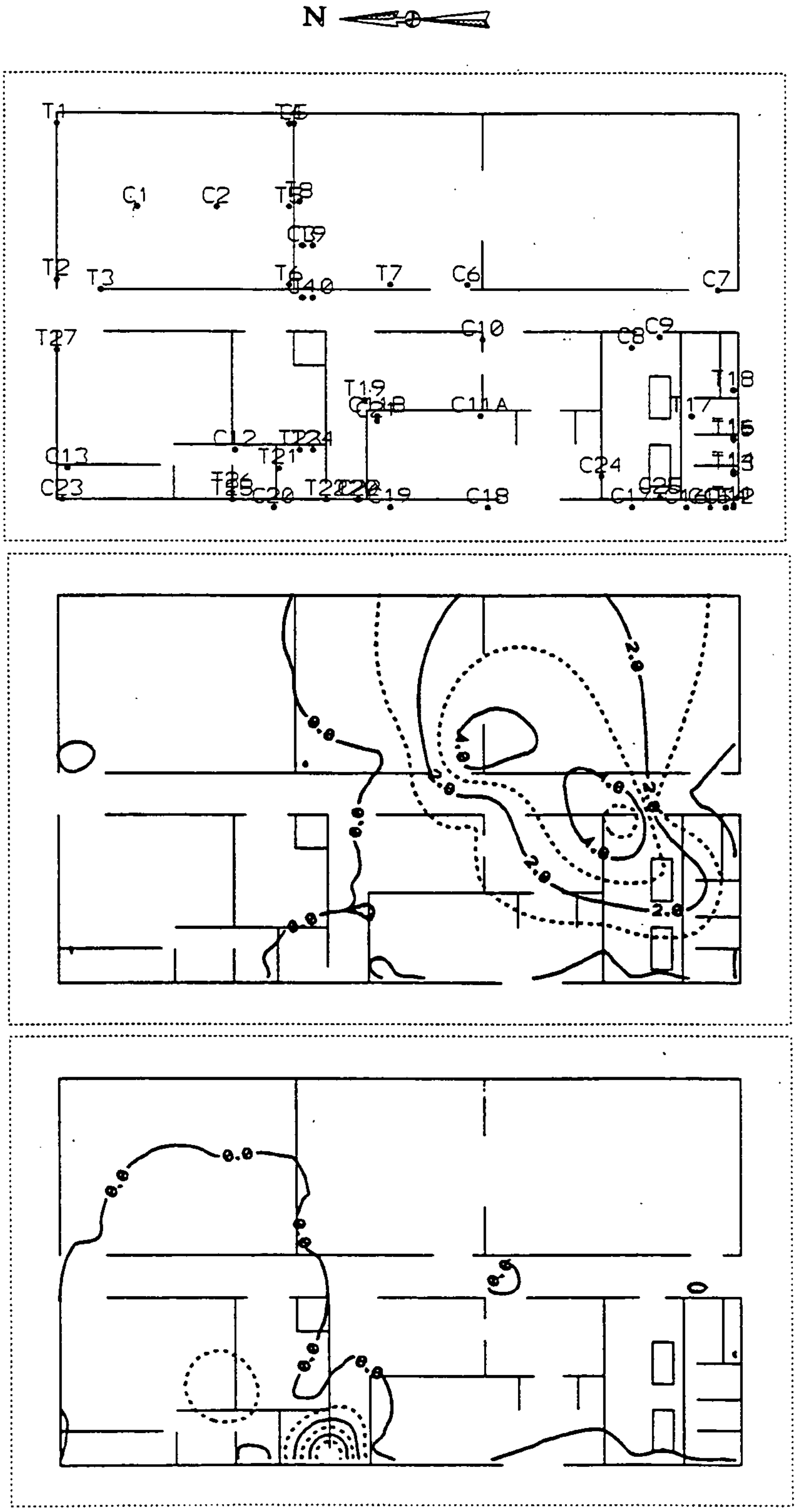


Figure 9. Application of spatial analysis techniques at the Caribbean Fruit Fly Mass Rearing Facilities in Gainesville, Florida. Top panel shows locations of 27 can (C) and 26 sticky traps (T) used to determine distribution of *Periplaneta* spp. of cockroaches. Centre panel shows that adults populations were restricted largely to 2 areas; both were large hollow steel doors with access holes caused by rust. Bottom panel shows that immature stages were located almost exclusively in one room. Subsequent examination revealed that populations were harboraging inside of hollow steel transport racks. See text for full description.

illustrate that, although *traditional* statistics failed to show a difference in these populations, *spatial statistics* clearly revealed that changes had occurred due to resource redistribution.

Use of probability contours, based on indicator data sets, has strong value at locating foci, because it is not inordinately influenced by extraordinarily high values, as can be the case with raw counts. These can be used as a guide in a management program for prescribing treatment, or for allocating and partitioning resources based on probabilities of reinfestation. This is best exemplified in the Caribbean Fruit Fly Rearing Facilities. Because traditional use of pesticides would be disastrous to the production of "healthy" sterile fruit flies for eradication programs, their management program must rely heavily on surveillance and judicious use of control agents. The biology of larger, peridomestic species of cockroaches (*Periplaneta* spp.) is such that elimination often can be achieved with baited traps, or with short-term placement of a toxic bait; however, placement of these is critical. Spatial statistics provides a convenient method of determining foci and success of treatment. Typically, they do not use probability contours because expression of their low trap counts as contours does not impart a bias. Spatial statistics has effectively demonstrated the concept of focality at the rearing facilities, and the impact of non-chemical intervention; doors, serving as harborage sites for larger stages, were replaced with models that preclude access by cockroaches.

In the near future, probability contours and spatial dynamics indices may have wide-spread commercial utility in several areas: documenting effective pest management, assessment of interventions in housedust mite abatement, confirmation of residue reduction (dirt, grease, duct debris, etc.), foci reduction. However, it is perhaps most useful immediately to researchers pursuing any of several research directions. For example, spatial dynamics indices could be used to evaluate foraging patterns or effectiveness of a given pattern of bait placement. They could be used to define effective areas of infection for point releases of biological control agents, or effectiveness of sanitation procedures and/or candidate allergen denaturation interventions.

In Gainesville, spatial dynamics indices are being used in developing strategies using non-traditional chemical interventions (repellents), non-chemical interventions (enhanced air flow, construction design, moisture management, etc.), and allergen management. This has particular value for developing repellents, in that spatial dynamics indices can define areas of stasis (values of zero) by comparing distribution patterns on different days. With a spatial dynamics index, there are innumerable ways that values of zero result. In the extremes, an area that was a poor environment on both sample dates will have a spatial dynamics index of zero (zero probability of a high count for the first comparison date minus zero probability for the second comparison date); similarly, good trap sites on both days will yield a zero spatial dynamics index (probability of 1 for both dates). Consequently, the combination of a zero contour and an indicator trap location (high value) reveal areas of stasis—locations where conditions are good for sustaining populations. These are the areas that require attention and must be rendered "inhospitable". In preparation of expanding research in this area, 3 additional buildings have been constructed; one of which was constructed without exterior walls, so that experimental materials or procedures can be evaluated as a management strategy for the next century.

ACKNOWLEDGMENTS

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