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Geostatistical Characterization of the Spatial Distribution of Adult Corn Rootworm (Coleoptera: Chrysomelidae) Emergence

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ABSTRACT Geostatistical methods were used to characterize spatial variability in western (*Diabrotica virgifera virgifera* LeConte) and northern (*Diabrotica barberi* Smith & Lawrence) corn rootworm adult emergence patterns. Semivariograms were calculated for adult emergence density of corn rootworm populations in fields of continuous corn and rotated (corn/soybean) corn. Adult emergence densities were generally greater for northern corn rootworms than for western corn rootworms. The spatial structures of the adult rootworm emergence were aggregated as described by spherical spatial models for western corn rootworm and exponential models for northern corn rootworm. Range of spatial dependence varied from 180 to 550 m for western corn rootworm and 172 to 281 m for northern corn rootworm. Semivariogram models were used to produce contour density maps of adult populations in the fields, based on grid sampling of actual emerging adult populations.

KEY WORDS *Diabrotica* spp., geostatistics, spatial variability, site-specific farming, semivariograms, kriging

WESTERN CORN ROOTWORM, *Diabrotica virgifera virgifera* LeConte, and northern corn rootworm, *Diabrotica barberi* Smith & Lawrence, are major pests of corn, *Zea mays* L., in the United States, accounting annually for \$350 million or more in insecticide application costs (Reed et al. 1991). Economical sampling or scouting strategies for corn rootworm are difficult to develop because populations often assume aggregated spatial distributions. This is particularly true for distributions of the relatively nonmobile soil-dwelling stages of corn rootworm, which vary spatially as a function of edaphic influences that mediate behavioral responses or cause mortality.

Corn rootworm development and phenology are temperature dependent and thus are influenced by spatially variable edaphic factors that affect soil temperatures, such as soil type, soil moisture, snow cover, or crop residue. Because the influence of environmentally mediated mortality factors may vary spatially as well as seasonally, the distributions of agriculturally important insects also vary spatially within a field as well as from one growing season to another. Although the numeric distributions of insect populations may be estimated from statistical indices based on frequency distributions, such as Moran's *I* statistic or Geary's *c* (Williams et al. 1992), these techniques do not measure spatial relatedness and do not allow correlation of population distributions with spatially variable environmental factors. Temperature-driven predictive models that are available for survival of corn rootworm eggs (Woodson and Gustin 1993, Woodson and Ellsbury 1994), development of the soil-dwelling stages

(Bergman and Turpin 1986, Jackson and Elliott 1988, Schaafsma et al. 1991), and the emergence phenology of adult corn rootworm (Elliott et al. 1990) do not account for spatial variation of within-field insect pest populations.

Geostatistical analysis provides an alternative approach for the characterization of spatially variable ecological data (Rossi et al. 1992; Williams et al. 1992), particularly for insect pest populations (Liebhold et al. 1993, Roberts et al. 1993, Rossi et al. 1993). A basic tool of geostatistics is the semivariogram (Fig. 1), which plots distance between sample pairs against a semivariance statistic (variation between those points) for all possible sample pairs at each distance. The semivariance for *N* sample pairs is calculated as $\gamma(h) = [1/2N(h)] \sum [z_i - z_{i+h}]^2$, where *h* is the lag distance between samples for variable *z*. For aggregated ecological data, such as adult corn rootworm emergence, the semivariance is expected to increase as the lag interval increases out to a distance where spatial dependence ceases to be detectable (range of aggregation). Omnidirectional or isotropic semivariograms plot the averages of semivariance values over all possible data pairs regardless of relative direction for each distance class. Where spatial structure varies with location or direction, anisotropic semivariograms may be calculated for sample pairs oriented in specific directions (Isaacs and Srivastava 1989, Rossi et al. 1992).

Certain features of semivariograms important for ecological interpretation of spatial data from insect populations are shown in Fig. 1. The theoretical lo-

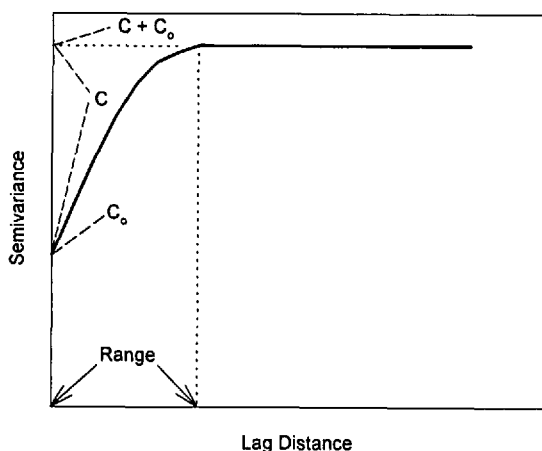


Fig. 1. Generalized semivariogram showing the range of spatial dependence, C_o , nugget effect; C , variability associated with spatial dependence; and $C + C_o$, sill.

calized discontinuity or nugget, C_o , is defined by the y-intercept and is interpreted as variability due to experimental error, distributional effects below the sampling scale of the study, and other random effects. The value of the semivariance at the 1st lag distance, termed the experimental nugget, is used as a more conservative estimate of the proportion of variability due to spatial structure (Williams et al. 1992). The range is the lag distance beyond which samples are considered spatially independent. The corresponding value of the semivariance at this point is termed the sill ($C_o + C$) and represents the combination of a nugget effect and variability (C) attributable to spatial dependence. The proportion of variability attributable to spatial dependence may be estimated as % variability = $C / (C_o + C)$, where C_o is the nugget and C is variability caused by spatial dependence as indicated by the distance from the nugget to the sill along the y-axis of Fig. 1.

Using geostatistical techniques, Schotzko and O'Keefe (1989) described within-field spatial nature of nymphal and adult populations of the lygus bug, *Lygus hesperus* Knight. Williams et al. (1992) demonstrated the aggregated and spatially variable structure of distributions of the soil-dwelling stages of the sugarcorn wireworm, *Limoniopsis californicus* (Mannerheim). Midgarden et al. (1993) applied geostatistical techniques to description of spatially structured, aggregated distributions of counts for corn rootworm adults trapped on sticky boards. Rossi et al. (1993) estimated northern corn rootworm densities and evaluated economic risk for treatment decisions on a regional scale by using geostatistical techniques and stochastic simulations of spatial variability applied to data taken from northwestern Iowa.

Site-specific management at the field level also should be possible, particularly for the nonmobile stages of soil-dwelling pests such as corn rootworms, provided that accurate knowledge of within-field spatial distributions of insect pest populations can be

economically determined (Ellsbury et al. 1996, 1997). Understanding of the spatial variability of the various corn rootworm stages will permit determination of sampling intensities needed to relate stage-specific spatial distributions to variability in edaphic factors that mediate mortality. Our objectives were to characterize spatial variability in adult corn rootworm emergence patterns on a field scale using semivariograms and to use semivariogram models to produce contour density maps of surviving adult populations in unsampled areas based on grid sampling of actual emerging adult populations.

Materials and Methods

Study Sites. The spatial distributions of western and northern corn rootworm adult emergence were characterized in 2 quarter-section fields. The 1st site, referred to as the Brookings field, was located in the southeast quarter, S24, T109N, R49W, latitude $44^{\circ} 13' 41''$ N and longitude $96^{\circ} 39' 04''$ W in Brookings County, SD. The Brookings field had a history of cultivation for grain and silage production. Populations of corn rootworms occur annually in this field even though past management practices have included application of terbufos at planting (7.3 kg/ha) for corn rootworm control. The 2nd site, designated the Elkton south field, was located in the southeast quarter, S8, T108N, R48W, latitude $44^{\circ} 10' 15''$ N and longitude $96^{\circ} 37' 25''$ W in Moody County, SD. The Elkton south field was farmed by narrow-row (57 cm), no-till methods in a corn-soybean rotation. Both study sites were 68.8 ha in size with 14.4 and 16.8 m of relief, respectively.

The western half of the Brookings field was bisected by a waterway extending as a broad arc from north to south and terminating in an unplanted wet area. Other unplanted wet areas were located on the eastern margin and in the extreme southeast corner, respectively. Two areas of the field in the extreme northeast corner and the southeast field margin, used for manure storage, also were not cultivated. There were no uncultivated areas in the Elkton south field, except for a narrow waterway running from southeast to northwest across the northeast quadrant.

Grid Samples. Adult corn rootworm emergence was monitored in the Brookings field during 1995 and 1996 and in the Elkton south field during 1995. Grid sampling was accomplished using emergence cages (0.5 m^2) similar to the design of Fisher (1984). The cages were installed in a hexagonal (offset) grid pattern during the 3rd wk of August in both years. Cages were centered over corn stalks in ≈ 1 m of row cut to within 10 cm of the ground. Numbers of northern and western corn rootworm adults that emerged were counted weekly in each cage from 27 July to 11 September 1995 and from 6 August to 23 September 1996. Voucher specimens have been deposited in the South Dakota State University Insect Collection.

The hexagonal grid sampling pattern was chosen because this design has provided better estimates than other sampling designs for assessing the spatial structure of insect populations (Schotzko and O'Keefe

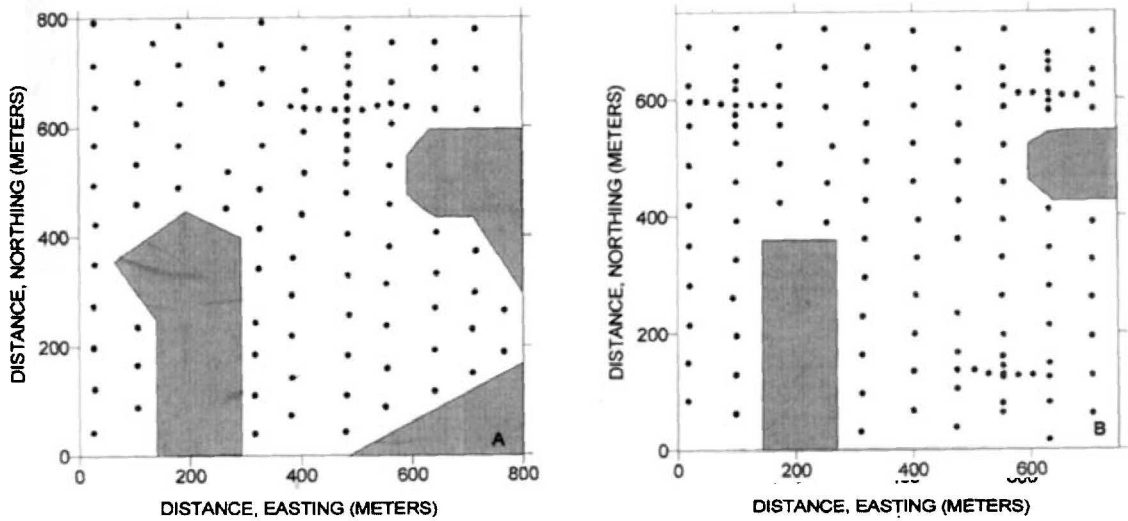


Fig. 2. Posting of georeferenced grid sampling points for emergence cages in (A) 1995 and (B) 1996 in the Brookings field showing cross-shaped cage installations used to obtain estimates of variation at lag distances <75 m. Unplanted areas are shown as shaded blocks.

1990, Williams et al. 1992). Ten sampling transects ≈ 75 m apart were established (Fig. 2). Sampling points within each transect also were ≈ 75 m apart and were offset from points in adjacent transects by ≈ 32.5 m to produce the hexagonal pattern. Sample sites that occurred in waterways, wet areas, or other unplanted areas of the field were relocated whenever possible to the nearest cultivated area of the field and at least 10 m from the edge of the uncultivated area. To provide samples at lag distances closer than 75 m for geostatistical analysis, additional sample points were established in cross-shaped patterns. Each arm of a cross contained 2 or 3 additional sample points aligned with the existing sample grid such that the minimum distance between points was ≈ 25 m. A single cross pattern was established in both fields in 1995, similar to the pattern shown in Fig. 2A for the Brookings field. Three cross-shaped arrays were located randomly in the Brookings field during 1996 (Fig. 2B).

Location of each sample point was determined using a differential global positioning system (Omnistar Model 6300a, Omnistar, Houston, TX) to obtain latitude and longitude values. These were converted to metric coordinates (± 1.5 m) referenced to the latitude and longitude of the southwest corner of the field. Emergence data were transformed to $\ln(z + 1)$ where necessary to stabilize variances. Spatial structure of adult emergence data was characterized as semivariograms calculated using GS+ (version 2.3, Gamma Design Software, Plainwell, MI). Semivariance values were divided by the population variance to allow comparison of semivariances on a common scale (Rossi et al. 1992). Directional semivariograms were calculated for 0, 45, 90, and 135° orientations with $\pm 22.5^\circ$ tolerance relative to 0° north. Models for the variograms were expressed as exponential, $\gamma(h) = C_o + C[1 - \exp(h/A_o)]$, or spherical, $\gamma(h) = C_o +$

$C[1.5(h/A_o) - 0.5(h/A_o)^3]$, functions. The model providing the best fit to the variogram, as indicated by r^2 values calculated by using GS+ v 2.3, was used to produce kriged estimates of adult emergence density at 30-m intervals. Kriged data were backtransformed in GS+ using the method of Haan (1977) to provide unbiased estimates. Contour maps of adult emergence densities were produced in Surfer (version 6, Golden Software, Golden, CO) by using grid files created from the kriged output from GS+.

Results and Discussion

Northern corn rootworms were collected in greater numbers than western corn rootworms in the Brookings field during both years of the study. Total numbers of northern corn rootworms collected were 1,839 and 3,008 compared with 644 and 503 western corn rootworms in 1995 and 1996, respectively. Northern corn rootworms were collected almost exclusively from the rotated Elkton south field. Omnidirectional semivariograms (Figs. 3, 4, and 5) showed spatial dependence among samples for both rootworm species.

Spherical models were used to describe the spatial structure of semivariograms for western corn rootworm adult emergence (Fig. 3A, $r^2 = 0.89$; Fig. 3B, $r^2 = 0.81$). The range of spatial dependence for western corn rootworm adult emergence was ≈ 550 m in the spherical model for 1995 data (Table 1) although there also was an initial plateau evident in the semivariogram (Fig. 3A) at a lag distance of ≈ 300 m. In 1996 a sill was evident (Fig. 3B) that corresponded to a range of spatial dependence of about 180 m. Adult western corn rootworm emergence showed theoretical nugget effects at ≈ 0.44 and 0.42 (y -intercepts) in 1995 and 1996, respectively, suggesting that $\approx 63\%$ of the vari-

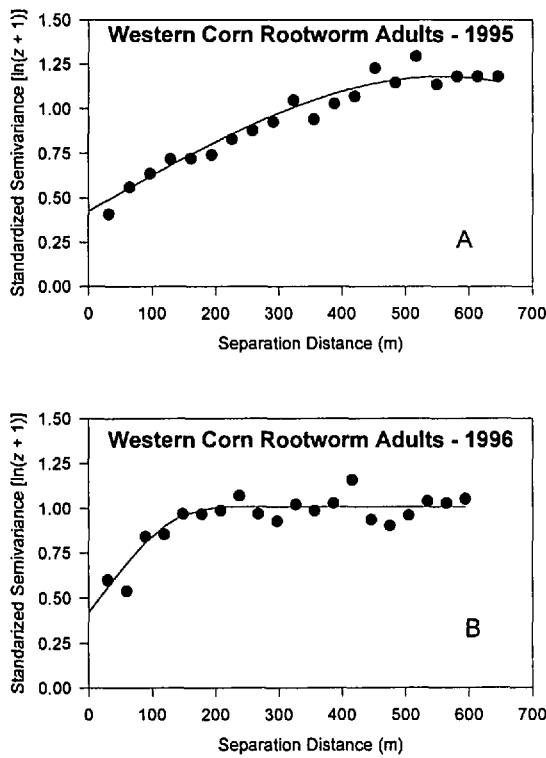


Fig. 3. Standardized omnidirectional semivariograms for western corn rootworm adult emergence density in (A) 1995 and (B) 1996 from the Brookings continuous corn field.

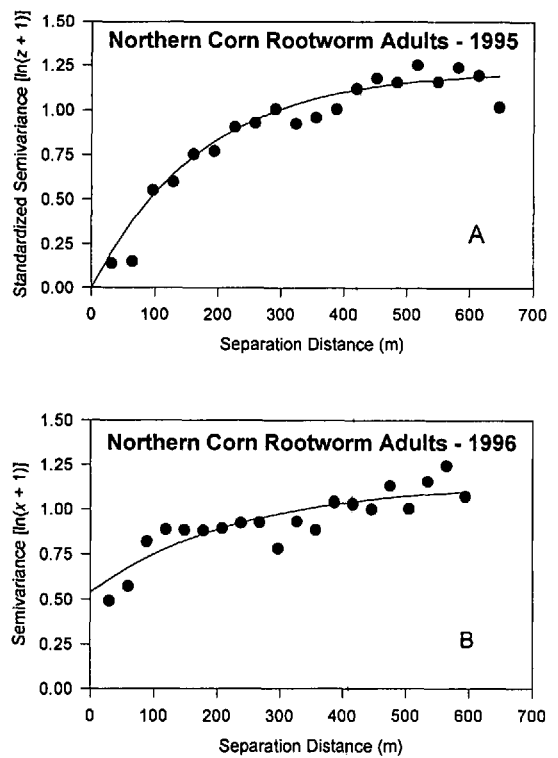


Fig. 4. Standardized omnidirectional semivariograms for northern corn rootworm adult emergence density in (A) 1995 and (B) 1996 from the Brookings continuous corn field.

ability among sample pairs in both years was explained by the spatial dependence of adult emergence. Spatial structure of northern corn rootworm adult emergence was best described by exponential models (Fig. 4A, $r^2 = 0.95$; Fig. 4B, $r^2 = 0.76$; Fig. 5, $r^2 = 0.86$). The range of spatial dependence is defined for exponential models as the distance at which the semivariance is 95% of the sill (Isaacs and Srivastava 1989). This value varied for northern corn rootworm from 66 m in the rotated corn to 231 m in the continuous corn during 1996. A nugget effect was not seen in northern corn rootworm data for 1995, but was present in the 1996 sample data. This indicated that, in 1995 and 1996, respectively, nearly 100% and $\approx 50\%$ of variability among sample pairs was explained by spatial dependence.

Contour maps of adult beetle emergence density per 0.5 m^2 are shown in Figs. 6, 7, and 8. These maps were produced using kriged data from grid samples of northern corn rootworm and western corn rootworm adult emergence. The highest incidence of both rootworm species during 1995 occurred in the northeast quadrant of the Brookings study site. The highest emergence of both rootworm species occurred in the same areas of the field, generally on higher, better drained ground found in the northern half of the field. This is particularly evident in Figs. 6A and 7A for 1995. In the Elkton south field, emergence of northern corn rootworm adults in 1995 occurred predominantly in the western half of the field (Fig. 8). Areas of both

fields where emergence was lowest also were often the most poorly drained sections, particularly in the southern half of the Brookings field and the northeast quadrant of the Elkton south field in areas along the waterway. Corn was either planted late or was slow to develop in these locations because of wet spring conditions that persisted through the developmental period of corn rootworms.

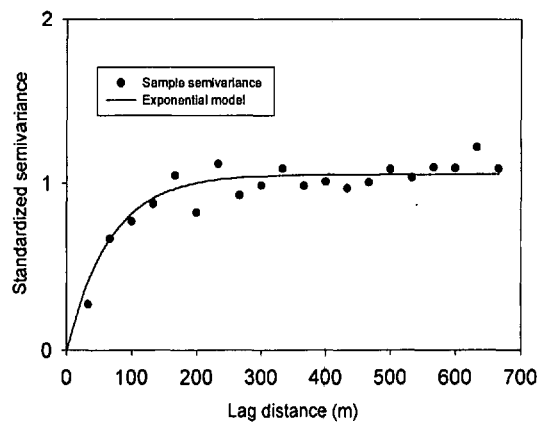


Fig. 5. Standardized omnidirectional semivariograms for northern corn rootworm adult emergence density in 1995 from the rotated corn cropping phase of the Elkton south field.

Table 1. Semivariogram models for spatial structure of western and northern corn rootworm adult emergence density

Field	Year	Species	Model	r^2	h	C_0	C_0+C	A_s
Elkton	1995	NCR	Exponential	0.86	33.3	—	1.06	66
Brookings	1995	WCR	Spherical	0.89	32.3	0.52	1.22	556
Brookings	1995	NCR	Exponential	0.95	32.3	—	1.01	172
Brookings	1996	WCR	Spherical	0.81	29.7	0.41	1.18	182
Brookings	1996	NCR	Exponential	0.76	29.7	0.54	1.14	231

NCR, northern corn rootworm. WCR, western corn rootworm; h , lag interval; C_0 , localized discontinuity; C_0+C , sill; A_s , range of spatial dependence for spherical models. For exponential models, range of spatial dependence is estimated as $3A_s$.

Directional semivariograms are shown in Figs. 9 and 10 for corn rootworm adult emergence. Small differences are evident in the directional variograms for 1995 shown in Fig. 9A and C. Semivariance values for the 90 and 135° directions increase gradually from the origin and level off at 0.75 to 1.0, corresponding to a range of spatial dependence of 200 to 300 m. Semivariances for the 0 and 45E directions in western corn rootworm data and in the 0° direction for northern corn rootworm data also increase gradually to ≈ 1.0 , but then continue to increase, reaching a value of nearly 2.0 at the greater lag distances. The sustained increase in variance with direction (i.e., from south to north [0°] and southwest to northeast [45°]), is consistent with the pattern of generally greater emergence for both species in the northeast corner of the Brookings field during 1995. Semivariance values in the 0 and 45° directions generally were highest at lag distances greater than ≈ 400 m in the directional semivariogram for 1995 northern corn rootworm emergence in the Elkton south field (Fig. 10). This

may be a reflection of higher emergence densities in the southwest quadrant of the Elkton south field. Anisotropy present in the directional semivariograms for the 2 rootworm species in 1995 data from the Brookings and Elkton south fields suggest that environmental (edaphic) factors (Rossi et al. 1992), possibly soil type or drainage, may have influenced the final adult emergence distribution in the same way for both species.

Directional semivariances for 1996 adult rootworm emergence in the Brookings field were similar for both rootworm species. Variances rise steeply at small lag distances to values that level off near 1.0 at lag distances of 100–150 m and then vary more or less randomly at greater lag distances. This spatial structure is reflected in the contour density maps (Fig. 6) that show more emergence in the northwestern and southwestern portions of the Brookings field in 1996 than was present in 1995. Edaphic factors probably influenced the final distribution of adult northern corn rootworm emergence in both fields.

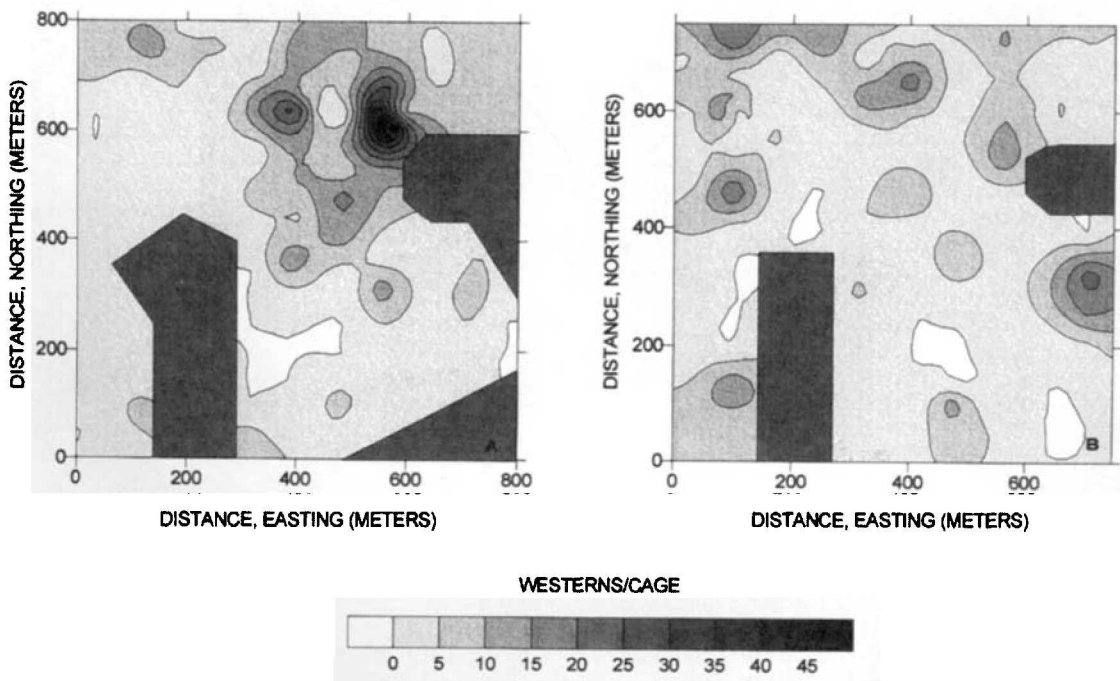


Fig. 6. Contour maps showing interpolated western corn rootworm adult emergence density for (A) 1995 and (B) 1996 from the Brookings continuous cornfield. Unplanted areas are shown as diagonal-line blocks.

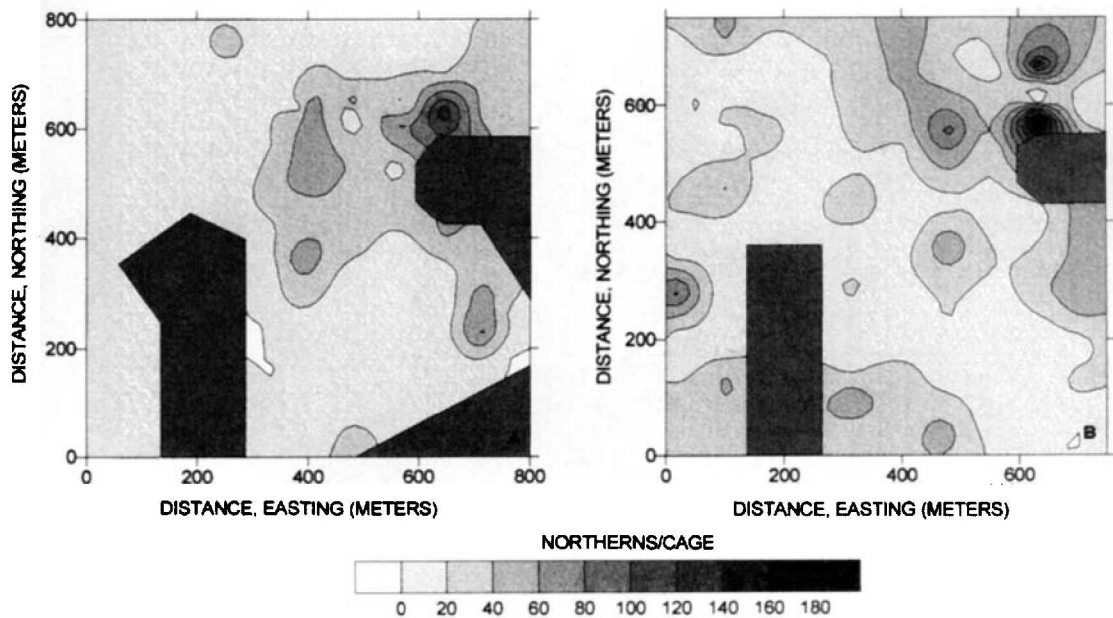


Fig. 7. Contour maps showing interpolated northern corn rootworm adult emergence density for (A) 1995 and (B) 1996 from the Brookings continuous cornfield. Unplanted areas are shown as diagonal-line blocks.

One possible explanation for low adult emergence in certain areas of each field may be excessive soil moisture that affects survival of corn rootworm larvae (Reidell and Sutter 1995). Soil conditions generally

were wetter in 1995 than in 1996 as reflected in the larger expanse of wet ground that was not planted in 1995 (Fig. 2). Areas with fewest adult corn rootworms emerging at both study sites also were areas with the poorest drainage and wettest conditions.

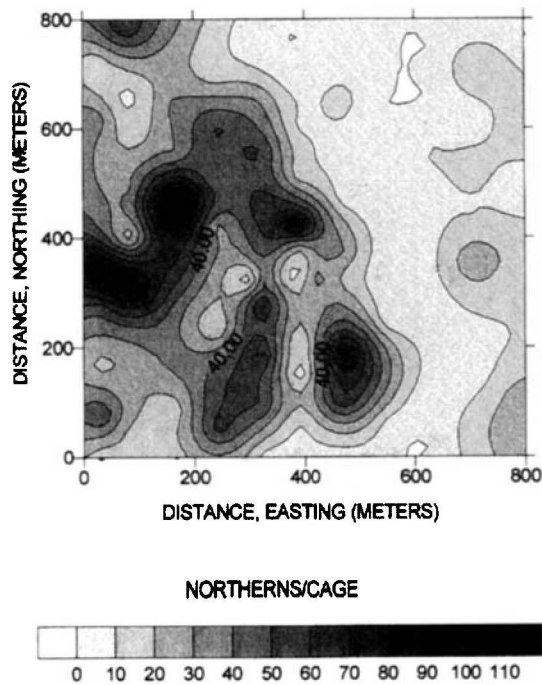


Fig. 8. Contour map showing interpolated northern corn rootworm adult emergence density for 1995 in the rotated corn cropping phase of the Elkton south field.

Because the Brookings field was treated with terbufos, edaphic influences on rootworm distribution also must be considered in terms of how they may have affected soil insecticide performance. High soil organic matter content is known to reduce performance of terbufos (Felsot and Lew 1989). Soils in low-lying, poorly drained areas generally contain more organic matter than do soils on well-drained slopes or summit landscape positions (Brady 1990). However, if reduced insecticide performance can be expected because of high organic matter content in soils occurring in low-lying areas, then the reduced adult corn rootworm emergence in low-lying areas of both the treated and the untreated fields of this study may have been the result of factors other than insecticide action, such as aggregated oviposition based on soil or other environmental factors.

Turpin et al. (1972) considered soil drainage among the significant edaphic factors that mediated rootworm infestation potential in their prediction equation for rootworm damage. They also concluded that predictive methods could be used to identify fields likely to require treatment. We suggest that such an equation could be further developed on a within-field scale to incorporate a predictive component for expected rootworm infestation and for insecticide efficacy based on site-specific soil properties within a field. This equation could then be used to drive site-specific soil insecticide application only to those areas

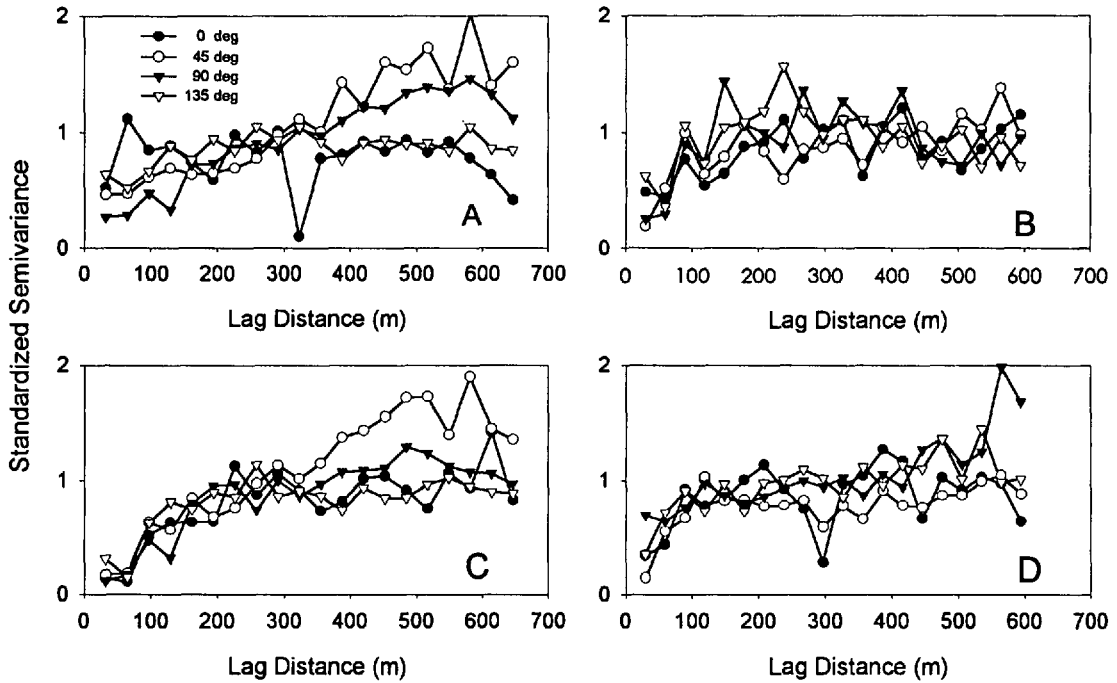


Fig. 9. Directional semivariograms calculated in the 0, 45, 90, and 135° orientations for adult emergence densities of western corn rootworms (A, 1995; C 1996) and northern corn rootworms (B, 1995; D, 1996) from the Brookings continuous corn field.

within a field where rootworm damage was likely and where the insecticide was likely to be most effective.

Site-specific prediction of rootworm activity also could be used to control precision planting of corn varieties. For example, if transgenic hybrids incorporating rootworm resistance become available, they would be planted within a field primarily in areas predicted to have high rootworm damage potential. The remaining areas of the field could be planted to a susceptible hybrid as part of a resistance management

strategy to provide refugia that will maintain a rootworm population susceptible to the transgenic resistance factor.

Recent developments in global positioning and geographic information technologies have created considerable interest in site-specific pest management systems. Geostatistical methods offer new approaches to the characterization, sampling, and management of insect pest populations (Rossi et al. 1992, Liebhold et al. 1993). The geostatistical technique of kriging, based on semivariogram properties (Isaaks and Srivastava 1989), can provide interpolated values for response variables, such as insect population density, at points not actually sampled. Applied to insect pest populations, these techniques should allow prediction of areas in fields where pest populations may be expected to exceed an action threshold. In the case of soil-dwelling pests, such as corn rootworms, geostatistical techniques may allow development of georeferenced maps of expected insect population density inferred from spatially variable mortality factors, soil types, or soil properties that are more easily sampled than are insect populations at the scale and intensity necessary for site-specific prediction.

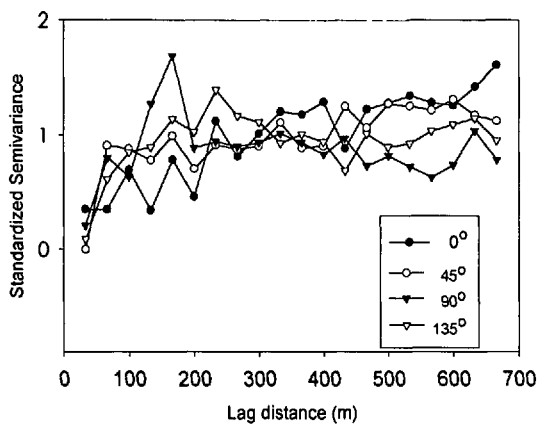


Fig. 10. Directional semivariograms calculated in the 0, 45, 90, and 135° orientations for adult emergence densities of northern corn rootworms for 1995 in the rotated corn cropping phase of the Elkton south field.

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