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DISSERTATION

Spatial Distribution of Weed, Nematode, and Western Corn Rootworm Egg Populations in Corn Fields

Submitted by

Dawn Y. Wyse-Pester

Department of Bioagricultural Sciences and Pest Management

In partial fulfillment of the requirements

For the Degree of Doctor in Philosophy

Colorado State University

Fort Collins, Colorado

Fall 2000

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October 25, 2000

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY **DAWN Y. WYSE-PESTER** ENTITLED SPATIAL DISTRIBUTION OF WEED, NEMATODE, AND WESTERN CORN ROOTWORM EGG POPULATIONS IN CORN FIELDS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Co-Advisor

Advisor

Department Head

ABSTRACT OF DISSERTATION

SPATIAL DISTRIBUTION OF WEED, NEMATODE, AND WESTERN CORN ROOTWORM EGG POPULATIONS IN CORN FIELDS

Knowing the distribution of pests in farmer-managed fields could help researchers develop reliable distribution maps that could be used for site-specific pest management. Two corn fields (71 and 53 ha) in eastern Colorado were sampled in 1997 and 1998 to investigate the spatial distribution of weed, plant-parasitic nematode, and western corn rootworm egg populations. Weed seedlings or mature plants were observed when corn reached the two-leaf, four-leaf, and physiological maturity stages. Weedy plants were observed on a 76.2 m square grid, a random-directed grid where sites were established at intervals of 76.2 m, and star configurations based on a 7.62 m grid within three 23223 m^2 areas. Pigweed seeds collected on the 76.2 m square and 7.62 m star grids were screened for triazine-resistance. Nematodes and rootworm eggs were sampled at all 76.2 m square grid sites prior to corn harvest each year. Spearman rank correlation was calculated for densities of nematode, rootworm egg, and triazine-resistant pigweed distributions with soil attributes of organic matter, sand, silt, and clay. Directional correlograms were calculated for 0, 30, 60, 90, 120, and 150 degrees from the crop row for weeds and calculated for 0, 45, 90, and 135 degrees for nematodes and rootworm eggs. Clay was positively correlated with resistant pigweed seedbank populations in both years. Seven

of 93 weed density distributions were spatially correlated up to 5 to 363 m. Spiral and stunt nematode densities were correlated with sand, silt, clay, and organic matter and 3 of 12 density distributions for spiral and lesion nematode densities were spatially correlated up to 97 to 845 m. Rootworm egg densities were not correlated to soil attributes but 1 of 4 distributions was spatially correlated up to 69 to 76 m. Due to the minimal detection of spatial correlation for weed seedling, nematode, or rootworm egg distributions in eastern Colorado corn fields, interpolated density maps should not be created from a 7.62 m grid for weed seedling infestations or a 76.2 m grid for nematode or rootworm egg infestations.

Dawn Y. Wyse-Pester
Department of Bioagricultural Sciences
and Pest Management
Colorado State University
Fort Collins, CO 80523
Fall, 2000

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DEDICATION

Hayden Allan Pester

Climb a mountain to reach the valley.

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CHAPTER 1

Infestation and Spatial Dependence of Weed Seedling and Mature Weed Populations in Corn Fields

ABSTRACT

The spatial distribution of a weed population within a field must be known if management inputs are going to be applied to infested areas of a field. With knowledge of the spatial arrangement of a weed population, cost-effective sampling programs and management strategies can be designed so inputs can be selected and applied to specific field areas where management is warranted. In 1997 and 1998, two center pivot irrigated corn fields (71 and 53 ha) in eastern Colorado weeds were sampled at 612 to 682 sites. Weed seedlings and mature weeds were counted within each field on a square grid at regular intervals of 76.2 m and at random locations (random increments of 5.08 m) within each of the 76.2 m intervals along the crop rows. In addition, weeds were observed at 7.62 m intervals within three random 23223 m^2 square field areas. Weed seedlings or mature weeds were observed when the crop was at the two-leaf stage (before postemergence treatment), four-leaf stage (after postemergence treatment), and physiological maturity (before harvest). Detected weed species were pigweed spp., nightshade spp., common puncturevine, kochia, common lambsquarters, common sunflower, prickly lettuce, shepherd's-purse, foxtail spp., field sandbur, barnyardgrass, Russian thistle, velvetleaf, Canada thistle, and common cocklebur. Nightshade spp. and pigweed spp. population mean densities tended to be greater than the other broadleaf or grass species populations in both fields and over the two years. Thus, under the current management procedures in these two fields only two (pigweed spp. and nightshade spp. populations) of the fifteen detected weed species had mean densities that fluctuated within a year for each field, while none of the fifteen species had mean densities that significantly differed between years. Out of 93 samples (a collection of sampling units

for a particular weed species that was detected, within a field, at a particular sampling time, and year) spatial dependence was detected for 7 samples for populations of field sandbur, pigweed spp., nightshade spp., and common lambsquarters. From the correlogram analysis it was determined that 18 to 72% of the variation in sample density was due to spatial dependence over a geographic distance up to 5 to 363 m for the six directions (0, 30, 60, 90, 120, 150 degrees from the crop row) examined. The lack of detectable spatial dependence for 86 of 93 samples with the employed sampling method suggests weed seedling densities in eastern Colorado irrigated corn fields are not correlated at separation distances equal to, or greater than 7.62 m and interpolated maps based on grid sampling at these scales should not be used because knowing a weed density at one field location would not provide any information about the weed density at an unsampled location.

Nomenclature: Corn, *Zea mays* L. ZEAMX; onions, *Allium cepa* L. ALLXP; sugar beet, *Beta vulgaris* L. BEAVA; pinto bean, *Phaseolus vulgaris* PHSVX; pigweed spp., *Amaranthus* spp.; nightshade spp., *Solanum* spp.; puncturevine, *Tribulus terrestris* L. TRBTE; kochia, *Kochia scoparia* (L.) Schrad KCHSC; common lambsquarters, *Chenopodium album* L. CHEAL; common sunflower, *Helianthus annuus* L. HELAN; prickly lettuce, *Lactuca serriola* L. LACSE; shepherd's-purse, *Capsella bursa-pastoris* L. Medic. CAPBP; foxtail spp., *Setaria* spp.; field sandbur, *Cenchrus longispimus* (Hack.) Fern CCHPA; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv. ECHCG; Russian thistle, *Salsola iberica* Sennen. & Pau SASKR; velvetleaf, *Abutilon theophrasti* Medic.

ABUTH; Canada thistle, *Cirsium arvense* (L.) Scop. CIRAR; common cocklebur, *Xanthium strumarium* L. XANST.

Key words: Spatial dependence, spatial structure, geostatistics, sampling, map, weed seedling infestation, spatial correlogram, weed distribution.

INTRODUCTION

Weed management inputs may be more efficiently applied if a producer had an accurate representation of the spatial distribution of weeds in a field. Management inputs could be applied only to field sections that require an input, thus reducing management costs and possibly increasing profits (Johnson et al. 1995). However, varying inputs within a field requires reliable distribution and density maps of the weed population. Weed distribution maps could be used to make decisions on where to treat, as well as the type and intensity of the input (management map). The accuracy of a weed distribution map and the usefulness of the resulting recommendation for various inputs (management map) will vary with the accuracy of estimating density and spatial distribution of each weed population (Audsley and Beaulah 1996).

The mean density and spatial distribution of a pest population can be estimated by sampling. A sampling program to estimate a pest infestation is a procedure that specifies how to collect information for an attribute at a particular time and sampling unit, which is placed at multiple locations within a field (Pedigo 1994). The accuracy of the sampling program must be balanced against the cost of gathering information if growers are to implement a particular sampling program (Buntin 1994). Investigating the characteristic

distribution of a weed population could lead to the development of reliable sampling programs for map generation.

To describe the spatial distribution of a weed population, frequency distribution methods such as Iwao's patchiness regression (Iwao 1968), Taylor's power law (Taylor 1961), and negative binomial (Ansocombe 1949) have been used. These methods only infer spatial relationships from the variance in density while the relative location of sample units is not considered. An alternate approach for the characterization of spatially variable ecological data, such as weed populations, is geostatistical analysis. Geostatistical techniques are a way to quantify and model the spatial dependence and map a phenomenon (Isaaks and Srivastava 1989). In particular, correlation, covariance, and semivariance functions have been employed to describe spatial distribution or continuity of pest populations (Cardina et al. 1996; Donald 1994; Heisel et al. 1996; Johnson et al. 1996; Midgarden et al. 1993; Mortensen et al. 1993; Mulugeta and Boerboom 1999; Turechek and Madden 1999; Weisz et al. 1995). These three functions use the value and location of each sampling unit to summarize the spatial dependence among points at various distances and directions across a field for a sample. When a pest such as a weed population exhibits spatial dependence, the value at one location and the values at other locations are correlated as a function of incremental distance (Rossi et al. 1992; Weisz et al. 1995).

Knowing more about the spatial distribution of weed populations will assist in determining whether interpolated weed maps can be created for site-specific management. A sampling program developed to help create an accurate distribution map of the population would need to include observations closer together than the distance of

spatial dependence (Weisz et al. 1995). However, if a scout wanted to estimate a mean density, a sampling program would need to include a number of observation pairs greater than the distance of spatial dependence (Weisz et al. 1995).

To date there have been few studies that have investigated the spatial dependence for weed seedling populations within entire fields. A study by Johnson et al. (1996) evaluated the spatial dependence of velvetleaf and common sunflower across two years in an 189 by 224 m field section in Nebraska. The range of spatial dependence for velvetleaf seedlings was 25 to 30 m when the field section was planted to either soybean or corn. However, the range of spatial dependence for common sunflower was up to 30 m when the field was planted to soybean, but decreased to 8 m the following year when planted to corn. Another study by Cardina et al. (1996) evaluated the spatial dependence of common lambsquarters and annual grass populations in two 25 by 90 m field sections that were planted in soybean for four years in Ohio. From this study it was determined that common lambsquarters populations were spatially dependent up to 63.4 m, while annual grass populations were spatially dependent up to 5.3 m when fields were moldboard plowed (Cardina et al. 1996). Both studies indicated the detected spatial dependence might be influenced by interactions of weed biology, local microenvironmental conditions, and agricultural practices (Cardina et al. 1996; Johnson et al. 1996).

Producers are requesting more detailed information on where and at what density a weed occurs in their field to make informed management decisions on what input to apply by location. The lack of field-specific data on the infestation and spatial distribution of weeds as well as the cost of sampling are obstacles to the development of

optimal sampling programs for growers to make site-specific management decisions. By knowing more about the weed infestation and distribution within fields, the cost and benefits of applying management inputs to selected field areas using management maps can be adequately assessed. The objective of this study was to investigate the spatial dependence of weed seedling and mature weed populations in two corn fields for two years in eastern Colorado to facilitate the future design of optimal sampling programs for creating reliable weed distribution maps that could be used for site-specific management.

MATERIALS AND METHODS

Field sites. Two grower-managed center-pivot irrigated corn fields (71 and 53 ha), located in Morgan County near Wiggins, Colorado, were sampled in 1997 and 1998. Soils present on both pivots included a Valentine sand (sandy, mixed nonacid, mesic Typic Ustipsamment), a Bijou loamy sand (coarse loamy, mixed, mesic Mollic Haplargid), and a Truckton loamy sand (coarse loamy, mixed, mesic Udic Argiustoll). The crop rotation for field 1 was corn (*Zea mays* L.) in 1993, corn (northwest half [crop rows were orientated in a northeast to southwest direction] and northeast quarter) and onions (*Allium cepa* L.) (southeast quarter) in 1994, corn in 1995, sugar beet (*Beta vulgaris* L.) in 1996, and corn in 1997 and 1998. Crop rotation in field 2 was sugar beet (northwest half) and pinto bean (*Phaseolus vulgaris*) (southeast half) in 1993, corn in 1994 and 1995, sugar beet in 1996 and corn in 1997 and 1998. Mean corn yields in 1997 were 10.9 and 13.0 t ha^{-1} for fields 1 and 2, respectively. Herbicides were selected and applied by each producer (Table 1). Preemergence herbicides were applied in 1997 (Table 1) to remove a winter wheat cover crop.

Sampling grids. Weed populations were sampled on three grid systems established within each field (Figure 1). Weed sampling sites (locations where sampling units were placed) were established within the crop rows on a 76.2 m square grid (Figure 1). Additional sampling sites (random-directed grid) were established within the direction of the crop row for each interval of 76.2 m (Figure 1). Each random-directed sampling site was established at randomly selected increments of 5.08 m within each 76.2 m interval. In addition, three 23223 m^2 square areas were randomly chosen in each field and 150 sites were established in a star configuration based on a 7.62 m square grid (star grids A, B, and C) (Figure 1). The random-directed and star grids were established to investigate spatial dependence at distances less than 76.2 m. Across all grids there was a total of 682 sampling sites in field 1 and 621 sites in field 2 in 1997, while in 1998 there were 679 sites in field 1 and 612 in field 2 (Table 2). All sampling sites per field (Table 2) were established and referenced with an OmniSTAR 7000[1] differential global positioning system.

Weed sampling. Weed seedlings or mature weeds by species were counted at each sampling site with a 1.52 by 0.15 m quadrat (sampling unit) in 1997 and 1998. The sampling unit was originally used to estimate weed densities for the determination of management decisions with a computer decision aid, WEEDCAM, (Schweizer et al. 1994). Weed sampling occurred when the crop was at a two leaf stage (before postemergence herbicide treatment), four leaf stage (after postemergence herbicide treatment), and physiological maturity (before harvest) (Table 3). In addition, for each species, three plants at physiological maturity were randomly selected to assess the

presence of flowers. The data was transformed by taking the square root and then analyzed using Proc Mixed analysis of variance (SAS 1988) to evaluate differences in mean densities for each weed species by field, sampling time, and year. Proc Mixed is a robust procedure for nonrandom sampling and nonnormal distributions. All tests were evaluated at $P \leq 0.05$.

Geostatistic analysis. The spatial distribution of each weed species per sample (a collection of sampling units for a particular weed species, within a field, at a particular sampling time, and year) was quantified by examining the spatial dependence of each population with spatial correlograms. A spatial correlogram is a plot of correlation coefficient values for sampling units (weed density) that are separated by various geographic distances (lag) and in a particular direction. Correlogram functions ($\rho(h)$) may be a better tool to quantify spatial dependence than variograms ($\gamma(h)$) because correlogram functions filter out local mean and variance trend effects that may occur over the sampling space (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). A correlogram value can only vary from +1 to −1 depending upon whether the correlation between sampling units is positive or negative (Rossi et al. 1992). Correlograms, unlike variograms, tend to have large coefficient values at short distances (h) and small values at longer distances (Isaaks and Srivastava 1989; Liehold et al. 1993; Rossi et al. 1992). Spatial correlograms were calculated with the following equation:

$$\rho(h) = \frac{1}{N(h)} \sum_{(i,j)|h_{ij}=h} (v_i * v_j - m_{(-h)} * m_{(+h)}) / \sigma_{(-h)}\sigma_{(+h)} \qquad (1)$$

where the tail mean $m_{(-h)}$ is given by:

$$m_{(-h)} = \frac{1}{N(h)} \sum_{i|h_{ij}=h} v_i \qquad (2)$$

and the head mean $m_{(+h)}$ is given by:

$$m_{(+h)} = \frac{1}{N(h)} \sum_{j|h_{ij}=h} v_j \qquad (3)$$

where N(h) is the number of pairs of points separated by h, h is the separation vector, v_i is the sample value at location i, v_j is the sample value at location j which is separated from location i by the vector h, and $\sigma_{(-h)}$ is the lag standard deviation of v_i, and $\sigma_{(+h)}$ is the lag standard deviation of v_j (Isaaks and Srivastava 1989). The $m_{(-h)}$ is the mean of the data values whose locations is –h away from some other data location and $m_{(+h)}$ is the mean of all data values whose locations are +h away from some other data location. For ease of interpretation, each correlogram was converted to variogram form (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995) by subtracting the correlation function from one, as demonstrated by the following equation:

$$\gamma(h) = 1.0 - \frac{1}{N(h)} \sum_{(i,j)|h_{ij}=h} (v_i * v_j - m_{(-h)} * m_{(+h)}) / \sigma_{(-h)}\sigma_{(+h)} \qquad (4)$$

After transforming each correlogram to variogram form, coefficient values tend to be small at short h and large at longer h (Isaaks and Srivastava 1989; Liehold et al. 1993; Rossi et al. 1992). For the remainder of the paper, the plots of the transformed correlogram function in variogram form will be represented as $\rho(h)$.

Important features of the correlogram in variogram form include the nugget, sill, and range (Isaaks and Srivastava 1989). The spatial discontinuity at distance 0 m is the nugget (Rossi et al. 1992). A non-zero nugget represents micro-scale variation below the

sampling scale and experimental or measurement error (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). The value at which the plotted points or individual coefficient values plateau is the sill (Rossi et al. 1992). When the correlation coefficient values of the transformed correlogram are plotted as a function of distance, the sill will be equal to one (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). The distance at which the correlation values level off to an asymptote or the sill is known as the range, which defines the maximum distance that sampling units (weed densities) remain correlated spatially (Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). The difference between the sill and the nugget represents the proportion of the total variation that is due to spatial dependence with the implemented sampling program (Rossi et al. 1992).

Spatial dependence for each sample (a collection of sampling units for a particular weed species that was detected, within a field, at a particular sampling time, and year) was analyzed at a total of six horizontal directions of 0, 30, 60, 90, 120, and 150 degrees from the crop rows. In addition, sampling units for each sample from the northwest and the southeast half of each field were examined separately for spatial dependence because previous crop rotations may have influenced the spatial distribution of weed populations. The angle of zero degrees was defined as along the crop row for each field (Figure 1). Lag increment was set at 9 m, which was the average separation distance among established sampling units in this study. The minimum number of paired sampling units at each lag was set to 30 to ensure an accurate estimate of variance (Journel and Huijbregts 1978; Liebhold et al. 1993; Rossi et al. 1992). In addition, each sample correlogram in variogram form was weighted by the number of pairs per lag. All spatial

analysis was conducted using SAGE95[2] geostatistical software. SAGE95 software is able to calculate multiple directional sample correlograms in variogram form and simultaneously model the experimental correlogram. All correlogram coefficients for the six investigated directions within a sample were simultaneously considered to estimate one nugget (spatial variation below the minimum distance between sampling sites, or experimental or measurement error for a sample) and a range for each direction. Each directional correlogram in variogram form was jointly fit with a spherical model for each direction and best fit was determined by least squares.

RESULTS AND DISCUSSION

Infestation. Fifteen weed species were detected in fields 1 and 2 (Tables 4 and 5). The number of detected weed species and corresponding densities fluctuated by field, sampling time, and year. A greater number of species were detected at the first sampling time than the other two sampling times by year in both fields (Tables 4 and 5). Pigweed spp., nightshade spp., common puncturevine, foxtail spp., and field sandbur in field 1 as well as field sandbur in field 2 were detected at each sampling time (Tables 4 and 5). The winter annual species, prickly lettuce and shepherd's-purse, were only detected at the last sampling because they were able to survive control by germinating late in the growing season (Tables 4 and 5).

For 55 samples, mean densities were less than 0.1 seedlings or mature plants per quadrat (Tables 4 and 5). Nightshade spp. (less than 0.1 to 9.7 seedlings or mature plants per quadrat) and pigweed spp. (less than 0.1 to 37.0 seedlings or mature plants per quadrat) population mean densities tended to be greater than the other broadleaf or grass species populations in both fields and over the two years.

Only for species of pigweed spp. and nightshade spp. did we find any significant difference in mean densities over the study period. Mean densities of pigweed spp. and nightshade spp. were greater in field 2 than field 1 in both years (Tables 4 and 5). Also there were significant differences in pigweed spp. and nightshade spp. mean densities between the first and second sampling times, and between the first and third sampling times in both fields and years. However, there was no significant difference in mean densities of either pigweed spp. or nightshade spp. between years for either field. Thus, under the current management procedures in these two fields only two (pigweed spp. and nightshade spp. populations) of the fifteen detected weed species had mean densities that significantly differed within a year for each field, while none of the fifteen species had mean densities that significantly differed between years.

Fluctuations in weed population densities between fields, years, and sampling times may be influenced by herbicide application, type, and timing of management inputs, environmental conditions, and the biology of each weed species (Cardina et al. 1997). In particular, pigweed spp. continued to germinate throughout the season in field 1 during 1997 (Table 4 and Figure 2). For the last sample time in 1997, only 32% of the sampling units were free of pigweed spp. (Table 4). Of the sampling units where a pigweed plant was present, 56% had one or more plants that were flowering and possibly returning seed to the weed seedbank (Figure 2). However, the majority of flower production was not in the southeast area of the field where pigweed seedlings first emerged early in the season (Figure 2A), but in the northwest area where pigweed seedlings emerged after postemergence herbicide application (Figure 2D). Although the majority of flower production occurred in the northwest area of the field (Figure 2D), the

majority of pigweed spp. emergence in 1998 occurred in the southeast portion of the field (Figure 2E), similar to 1997 (Figure 2A). Knowing that the pigweed spp. population germinated in similar locations in 1997 (Figure 2A) and 1998 (Figure 2E) may indicate that sampling to map the pigweed infestation may not be necessary every year. Similarly, a study by Gerhard et al. 1999 (weed seedling populations examined in a corn-soybean rotation) and another study by Walter 1996 (weed seedling populations examined in a spring wheat- winter wheat-sugar beet rotation) both determined that selected broadleaf species were persistent, thus suggesting that weed maps could be used to predict future seedling distributions thereby minimizing sampling efforts.

Weed-free sampling units ranged from 1 to 100% among fields and years. Fifty-four of 58 samples in field 1 (Table 4) and 61 of 65 samples in field 2 (Table 5) had 90% or more weed-free sampling units. The large percentage of weed-free area in both fields was similar to a study conducted by Johnson et al. (1995) where weed populations were studied in small field portions in Nebraska. They documented that management inputs could be reduced 30 to 70% by applying inputs only to areas infested with a weed. However, to assess the costs and benefits of implementing site-specific herbicide applications it will be important to assess not only the amount of weed-free area but also its spatial arrangement (Audsley 1993). Samples where 90% or fewer sampling units were weed-free occurred for pigweed spp. at the first, second, and third sampling time in field 1 during 1997, nightshade spp. at the third sampling time in field 1 during 1998, and for pigweed spp. and nightshade spp. at the first sampling time in field 2 during 1997 and 1998 (Tables 4 and 5). For these fields, a uniform application may be better than site-

specific management because the majority of the sampling units were infested with one or more pigweed plant.

Spatial dependence. Spatial dependence (weed densities at one location were correlated as a function of incremental distance and direction to weed densities at other locations) was detected for 7 of 93 samples for pigweed spp., nightshade spp., field sandbur, and common lambsquarters (Table 6). These species were the most abundant in both fields (Tables 4 and 5). Spatial dependence was only detected for samples before a postemergence herbicide application, with the exception of the pigweed spp. sample in field 1 at the second sampling time during 1997 (Table 6). Based on these samples, the distance that weeds were spatially dependent was up to 5 to 363 m for the six directions that were examined (Table 6). However, 86% of the ranges for the six directions were less than 100 m and the average range for the six directions was 57 m. Detected ranges in this study were similar to studies that examined the spatial dependence of common lambsquarters (Cardina et al. 1996), as well as common sunflower and velvetleaf seedlings (Johnson et al. 1996). In these studies, the range of spatial dependence was from 4.5 to 80 m (Cardina et al. 1996; Johnson et al. 1996). In particular, Cardina et al. (1996) determined common lambsquarters was spatially correlated up to a distance of 4.5 to 63.4 m, depending on whether soybean fields were subjected to no-till or moldboard plowing for four years.

Even though spatial dependence was detected for 7 samples, the variability in weed density between sampling units at very small distances (less than 9 m) was often high. Nugget values ranged from 0.28 to 0.82, indicating 72 to 18% of the variation in

sample density was due to spatial dependence over a geographic distance of 5 to 363 m, depending on direction (Table 6). In addition, since each correlogram by direction for a particular sample was simultaneously fit with a spherical model, most of the information for estimating the nugget and range has come from directions where sampling sites were separated at closer distances.

Specifically, spatial dependence was detected for pigweed samples in field 1 in 1997 at the second sampling time and in field 2 during 1998 at the first sampling time (Table 6). The longest detected range for the six directions evaluated was 363 m at 120 degrees from the crop row for pigweed spp. in field 1 at the second sampling time during 1998, but only 18% of the variation was due to spatial dependence (Table 6).

Spatial dependence for field sandbur was detected in both fields. Field sandbur was the only species in which spatial dependence was detected in the same field both years (Table 4 and Figure 3). In field 1 during 1997, field sandbur population had a nugget of 0.51 (Figure 3A) and ranges of 13 to 98 m for the investigated directions, while in 1998 the nugget decreased to 0.28 (Figure 3B) with ranges of 5 to 30 m for the investigated directions (Table 6). Between years and along the direction of the crop row, observed field sandbur densities were related up to 98 m during 1997, but only related to 30 m during 1998 in field 1 (Figure 3). A correlation coefficient of zero occurred for the sample of field sandbur when all sample units were field sandbur-free for a particular lag distance (Figure 3D). For field 2 during 1998, the nugget was 0.55 while the range of spatial dependence was 18 to 61 m depending on direction (Table 6). For these three field sandbur samples, spatial dependence was detected at greater distances in the direction of the crop rows (30 to 98 m) than the other five directions (5 to 47 m),

suggesting field sandbur dispersal may occur more easily down the crop rows than across them (Table 6). Greater ranges in the direction of the crop rows may be due to crop management, water, and wind (Howard et al. 1991; Johnson et al. 1992; Nordbo et al. 1994). Similarly, weed densities were more similar in the direction of the crop row in a study conducted by Johnson et al. (1996). Future sampling plans to adequately map the spatial distribution of weeds in other eastern Colorado fields should consider placing sampling units at greater separation distances in the direction of the crop rows then across crop rows.

Spatial dependence was not detected for common lambsquarters when all sampling units were evaluated within this field. Common lambsquarters density was correlated up to 43 m in the direction of the crop rows in field 2 during 1998 when only the sample units from the northwest half of the field were evaluated (Table 6 and Figure 4A). Detecting spatial dependence only from the sample units from the northwest half may be due to differences in crop rotations. In 1993, the northwest half of field 2 was planted in sugar beet, while the southeast half was planted in pinto bean. The impact of crop rotation on weed infestation was investigated by Dotzenko et al. (1969), and they indicated that sugar beet grown after beans in Colorado was always more weed-free than sugar beet grown after sugar beet, corn, or barley. Along with the difference in rotation, herbicide selectivity may have promoted the infestation of common lambsquarters in the northwest area when planted in sugar beet during 1993. Common lambsquarters control may not be as complete when the field is planted in sugar beet as when planted in a crop such as pinto bean because herbicide selectivity is often lower for weeds that occur

within the same plant family as the crop (sugar beet and common lambsquarters are in the Chenopodiaceae family) (Dotzenko et al. 1969).

Next, spatial dependence was detected for nightshade spp. in field 2 during 1998 before a postemergence herbicide was applied. The nugget was 0.69 and ranges for the six directions were 55 to 104 m (Table 6). Even though nightshade spp. plants were detected in most of the sampling units (only 17% were nightshade-free) (Table 5), 31% of the sample variation was due to spatial dependence up to 55 m in the direction of the crop rows (Figure 4).

Spatial dependence was not detected for many weed samples. The correlograms for remaining samples often exhibited a pure nugget effect where there was no correlation between sampling units at any distance and none of the variation in density was due to spatial dependence. This implies the spatial distribution of these species may be random at sampling distances (Wallace et al. 1994) used in our study and spatial dependence may occur at much smaller separation distances. Thus, the failure to detect spatial dependence does not necessarily indicate the distribution is random at other scales. For mapping purposes, knowing a weed density at one field location for a sample with a pure nugget effect would not provide any information about the weed density at an unsampled location. Thus, an interpolated map may be inaccurate (Issaks and Srivastava 1989; Weisz et al. 1995).

The lack of spatial dependence or presence of large nugget effects may have been due to inadequate sampling unit size and placement, or human measurement error (sampling error) (Isaaks and Srivastava 1995; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). As mentioned previously, the smallest separation distance may have

been too large to detect spatial dependence. Processes of seed dispersal, germination, and mortality events may operate below the average separation distance (9 m) that was observed in this study. Also, Weisz et al. (1995) determined sampling unit size might explain the frequency of finding pure nugget effects. When the Colorado potato beetle (Coleoptera: Chrysomelidae) was resampled with a larger sampling unit, the experimental error decreased while precision increased, and spatial dependence was detected (Weisz et al. 1995). Sampling with a sampling unit designed for estimating a mean density, not for mapping, may have been inadequate to detect spatial dependence for many of the weed populations in these fields.

The number and placement of sampling units was constrained by the limited amount of time, resources, and multiple goals of a large multidisciplinary research project (Heermann et al. 1999). Due to these constraints, there may have been an insufficient number of sampling units at separation distances below 76.2 m to detect spatial dependence for many of the weed species. In order to adequately assess whether spatial dependence exists for these species, more sampling units need to be placed at shorter separation distances (less than 76.2 m and possibly less than 7.62 m throughout the entire field in multiple directions). In addition, future studies may need to investigate the impact of sample unit size on experimental error on the detection of spatial dependence for weed populations. Increasing the size of the sample unit tends to decrease the variability between sampling units and increase sampling precision (Isaaks and Srivastava 1989; Weisz et al. 1995). However, future studies that investigate sampling unit size in the detection of spatial dependence will likely need to consider its impact on human sampling error and grower adoption.

Knowing the spatial dependence of weeds is important as we set out to identify cost-effective sampling programs that a grower could implement to map the spatial weed distribution in fields. Future sampling methods to evaluate spatial dependence of weed seedlings in eastern Colorado corn fields should include observing seedling densities at separation distances less than 7.62 throughout the entire field in multiple directions. Observing weed densities within the distance of the ranges by direction may enable the producer to adequately estimate weed densities at unsampled locations and create a sufficiently accurate interpolated weed distribution map.

However, total weed seedling or mature plant sampling programs for map generation should not be developed for irrigated corn fields in eastern Colorado with only the information gathered in this study. In order to create an accurate distribution map of the total weed infestation, weed populations must exhibit spatial dependence. However, for only 7 of 93 samples could an interpolated map be created. There is likely not enough information to develop sampling programs for map generation for the total weed infestation that may occur in eastern Colorado corn fields because of the minimal detection of spatial dependence. In addition, for the 7 samples where spatial dependence was detected, weed densities were related at short distances well below 363 m for the six directions that were observed, indicating that numerous weed observations would be necessary to create an accurate map for only a few species.

Future direction. This study was unique because it evaluated the entire weed seedling and mature plant population over two entire fields for two years. Grid sampling may be too labor intensive and expensive at this time to adequately map the total weed infestation

in an eastern Colorado irrigated corn field. It has been determined that the average cost of counting and identifying weed seedlings is 0.08 dollars per quadrat (Wiles and Schweizer 1999). For example, it may cost 128 dollars to count and identify field weed seedling in field 2 on an 18 m grid (smallest detected range of spatial dependence) when 1,600 sites would be observed at a cost of 0.08 dollars / observation.

One method to reduce sampling effort and expense may be to better understand the impact of field attributes and management inputs on weeds. The relationship between the frequency of weeds and soil properties was studied by Anderson et al. (1991), Bigwood et al. (1998), and Chauvel et al. (1989). From our study and others like it, there may be possibilities of directing sampling effort to areas that promote a weed infestation (soil characteristics, weed seed banks, and environmental conditions), thus minimizing sampling time and expense. Also, future research to quantify spatial weed patterns may move away from standard grid sampling to remote image analysis (Chaperon et al. 1999; Thornton et al. 1990; Rinds et al. 1999). A study by Thornton et al. (1990) used aerial photographs to determine the percentage of the area infested with wild oats (*Avenal factual* L.) in a winter wheat field. Most of the remote weed sensing work has occurred for cereal crops and fallow fields (Lamb and Weldon 1998; Rew et al. 1996; Thornton et al. 1990) because limited cover allows seedlings to be detected readily. Until remote imaging becomes a useful tool to detect weed seedling populations in various types of cropping situations and stages, there is a need to design sampling programs to accurately map the true weed seedling population in a field.

SOURCES OF MATERIAL

[1]OmniSTAR, Inc., 8200 West glen, Houston, TX 77063.

[2]Isaaks & Co. 1995. SAGE95. 205 E. 3rd Ave. Suite 300 San Mateo, CA 94401, USA.

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Table 1. Herbicides applied to fields 1 and 2 during 1997 and 1998.

Field	Year	Application Time	Herbicide treatment	Rate
				Kg ai ha^{-1}
1	1997	PRE[a]	Glyphosate + Atrazine	1.12 + 2.02
		POST	(Nicosulfuron + Rimsulfuron + Atrazine)	(0.84)[b]
1	1998	PRE	Metolachlor + Cyanazine	2.18 + 2.24
		POST	(Nicosulfuron + Rimsulfuron + Atrazine) + diglycolamine	(0.84) + 0.14
2	1997	PRE	Glyphosate + Metolachlor	1.12 + 1.94
		POST	Pyridate + Atrazine	0.91 + 2.02
2	1998	POST	(Nicosulfuron + Rimsulfuron + Atrazine) + Pyridate	(0.84) + 0.49

[a] Abbreviations: PRE, preemergence; POST, postemergence.

[b] Items in parentheses indicate a premix.

Table 2. Number of sampling units established by field, grid, and year.

	Field 1		Field 2	
Grid	1997	1998	1997	1998
	No. of sampling units			
Regular	122	121	91	86
Random-directed	110	108	80	76
Star A	150	150	150	150
Star B	150	150	150	150
Star C	150	150	150	150
Total	682	679	621	612

Table 3. Weed seedling sampling times and dates.

Field	Sampling Time	Date	
		1997	1998
1	Before postemergence treatment	06-03	05-27
	After postemergence treatment	06-28	06-18
	Before harvest	09-29	09-16
2	Before postemergence treatment	06-03	05-28
	After postemergence treatment	06-20	06-19
	Before harvest	09-23	09-19

Table 4. Weed infestations in field 1 during 1997 and 1998.

		Weed density							
		Mean (Standard deviation)		Median		Maximum		Weed-free sampling units	
Species	Sampling Time	1997	1998	1997	1998	1997	1998	1997	1998
		No. quadrat^{-1}						%	
Nightshade spp.	1	0.5 (3.8)	0.2 (1.0)	0	0	87	11	90	92
Pigweed spp.		1.9 (8.7)	1.0 (0.4)	0	0	99	42	71	80
C. Lambsquarters		< 0.1 (0.2)	< 0.1 (0.1)	0	0	6	1	99	99
C. Sunflower		< 0.1 (0.3)	———	0	—	7	—	99	100
Puncturevine		0.1 (0.7)	0.1 (1.0)	0	0	15	15	98	96
Kochia		0.1 (1.2)	———	0	—	32	—	99	100
Russian Thistle		< 0.1 (< 0.1)	< 0.1 (0.2)	0	0	1	2	99	97
Canada Thistle		< 0.1 (0.1)	———	0	—	2	—	99	100
Foxtail spp.		< 0.1 (0.6)	< 0.1 (0.1)	0	0	14	2	97	99
Field Sandbur		0.3 (3.0)	0.2 (1.5)	0	0	67	33	91	96
Barnyardgrass		< 0.1 (0.3)	< 0.1 (< 0.1)	0	0	5	1	97	99
C. Cocklebur		———	< 0.1 (0.1)	—	0	—	3	100	99
Nightshade spp.	2	0.1 (0.9)	< 0.1 (0.1)	0	0	18	2	96	99
Pigweed spp.		0.8 (2.5)	0.1 (0.4)	0	0	27	5	73	93
Velvetleaf		< 0.1 (< 0.1)	< 0.1 (0.1)	0	0	1	1	96	99
Puncturevine		0.2 (2.0)	< 0.1 (0.2)	0	0	32	4	95	98
Kochia		< 0.1 (0.1)	———	0	—	1	—	96	100
Russian Thistle		———	< 0.1 (0.2)	—	0	—	2	100	98
C. Cocklebur		———	< 0.1 (0.1)	—	0	—	2	100	99
Foxtail spp.		0.1 (0.8)	< 0.1 (0.6)	0	0	17	16	95	99
Field Sandbur		0.1 (1.5)	0.1 (0.8)	0	0	34	21	94	98
Nightshade spp.	3	0.4 (1.3)	0.1 (0.5)	0	0	15	6	76	94
Pigweed spp.		2.9 (4.3)	0.6 (1.7)	1	0	42	36	32	64
Puncturevine		< 0.1 (0.1)	< 0.1 (0.1)	0	0	1	3	96	99
Prickly Lettuce		< 0.1 (0.2)	< 0.1 (0.2)	0	0	2	1	94	97
Shepherd's-purse		0.1 (0.3)	< 0.1 (0.2)	0	0	3	3	90	98
C. Lambsquarters		< 0.1 (0.6)	< 0.1 (0.1)	0	0	14	1	96	99
Foxtail		0.2 (1.3)	< 0.1 (0.1)	0	0	22	2	90	99
Field Sandbur		0.1 (0.7)	< 0.1 (0.1)	0	0	16	2	94	99

Table 5. Weed infestations in field 2 during 1997 and 1998.

		Weed density							
		Mean (Standard deviation)		Median		Maximum		Weed-free sampling units	
Species	Sample time	1997	1998	1997	1998	1997	1998	1997	1998
		No. quadrat^{-1}						%	
Nightshade spp.	1	5.1 (18.0)	9.7 (18.3)	0	4	292	138	59	17
Pigweed spp.		3.5 (7.5)	37.0 (23.3)	1	32.5	67	135	42	1
C. Lambsquarters		0.3 (3.5)	2.0 (8.3)	0	0	68	104	94	75
C. Sunflower		< 0.1 (0.1)	0.1 (0.6)	0	0	2	15	99	97
Puncturevine		< 0.1 (0.6)	< 0.1 (0.1)	0	0	15	1	99	98
Kochia		< 0.1 (0.1)	< 0.1 (0.1)	0	0	2	1	99	98
Russian Thistle		0.1 (0.4)	0.3 (0.7)	0	0	3	4	91	82
Foxtail spp.		———	0.1 (0.5)	—	0	—	8	100	94
Field Sandbur		< 0.1 (0.6)	0.1 (0.5)	0	0	12	6	97	90
Barnyardgrass		———	0.1 (3.3)	—	0	—	79	100	98
C. Cocklebur		< 0.1 (0.1)	< 0.1 (0.1)	0	0	1	1	99	99
Nightshade spp.	2	< 0.1 (< 0.1)	———	0	—	1	—	99	100
Pigweed spp.		< 0.1 (0.2)	———	0	—	3	—	99	100
Puncturevine		< 0.1 (0.1)	———	0	—	2	—	99	100
C. Lambsquarters		< 0.1 (0.1)	———	0	—	3	—	99	100
C. Sunflower		< 0.1 (0.1)	———	0	—	1	—	99	100
Foxtail spp.		< 0.1 (< 0.1)	< 0.1 (0.1)	0	0	1	1	99	99
Field Sandbur		< 0.1 (0.4)	< 0.1 (0.1)	0	0	6	1	98	99
Nightshade spp.	3	< 0.1 (0.1)	0.1 (0.2)	0	0	1	2	98	96
Pigweed spp.		0.2 (0.8)	0.2 (0.6)	0	0	8	5	86	87
Prickly Lettuce		< 0.1 (0.1)	< 0.1 (< 0.1)	0	0	1	1	98	98
Shepherd's-purse		0.1 (0.3)	< 0.1 (0.1)	0	0	3	2	92	97
C. Lambsquarters		———	< 0.1 (0.1)	—	0	—	3	100	98
Foxtail spp.		< 0.1 (< 0.1)	< 0.1 (< 0.1)	0	0	1	1	99	98
Field Sandbur		< 0.1 (0.2)	< 0.1 (0.1)	0	0	3	1	99	99

Table 6. Correlograms for samples where spatial dependence was detected in fields 1 and 2 during 1997 and 1998.

Field	Year	Sampling Time	Species	Nugget	Range Degrees[a] (clockwise) from the row direction 0	30	60	90	120	150
					m					
1	1997	1[b]	Field sandbur	0.51	98	21	14	13	16	31
1	1997	2[c]	Pigweed	0.82	94	75	80	118	363	190
1	1998	1	Field sandbur	0.28	30	10	6	5	6	11
2	1998	1	Field sandbur	0.55	61	26	18	18	23	47
2	1998	1	Pigweed	0.68	80	140	116	70	57	59
2	1998	1	Nightshade	0.69	55	104	60	38	33	36
2	1998	1	Lambsquarters[d]	0.43	43	34	25	22	25	33

[a]Direction from the crop rows

[b]Before a postemergence herbicide application.

[c]After a postemergence herbicide application.

[d]Only sampling units on the northwest field section.

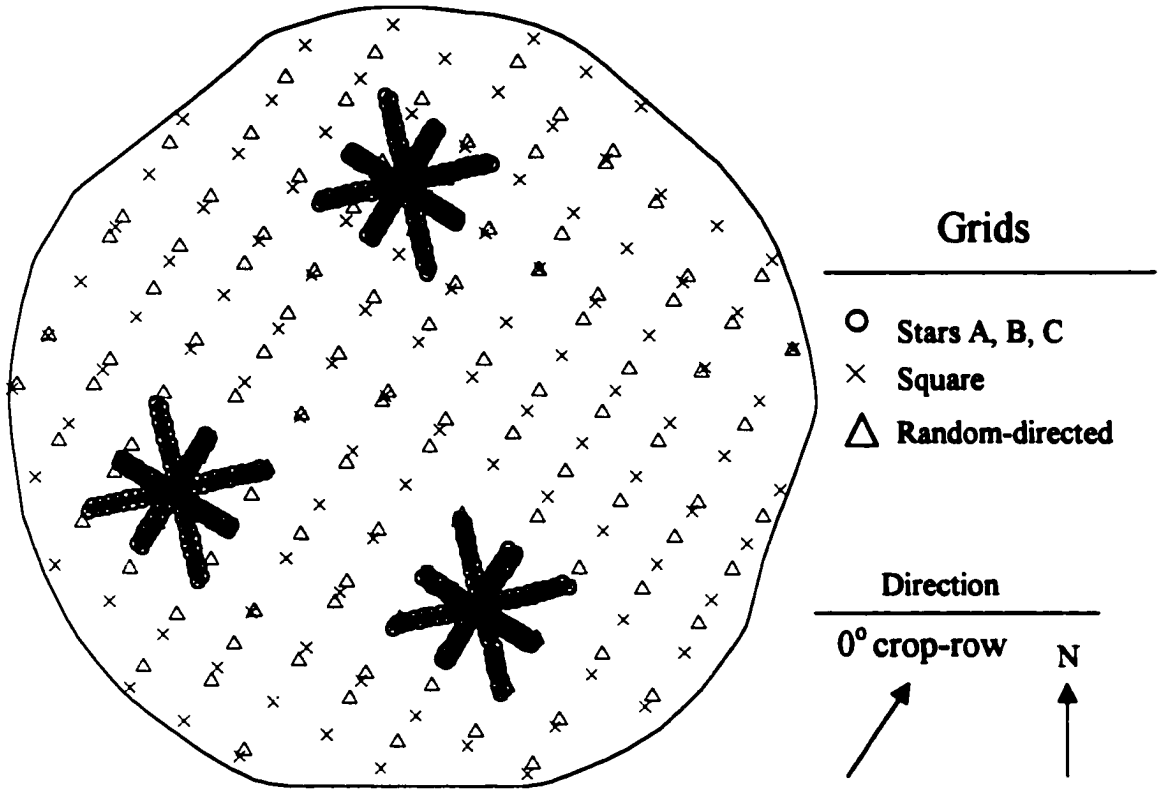

Figure 1. Placement of sampling units in field 1. Sampling unit placement was similar in field 2.

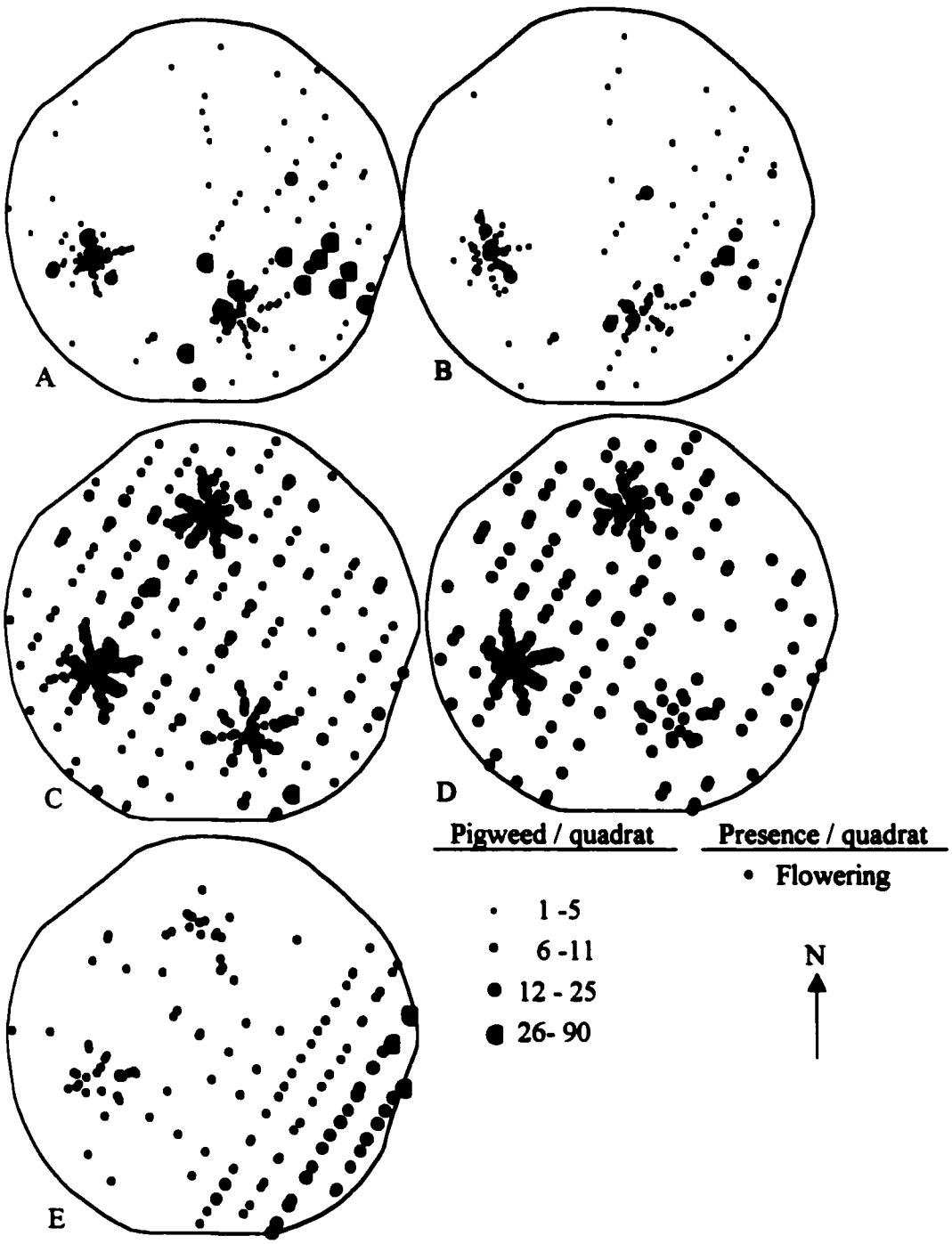

Figure 2. Pigweed spp. seedling distribution in field 1 during 1997 at the first (A), second (B) and third (C) sampling time, presence of flower structures (D), and seedling distribution in 1998 at the first sampling time (E).

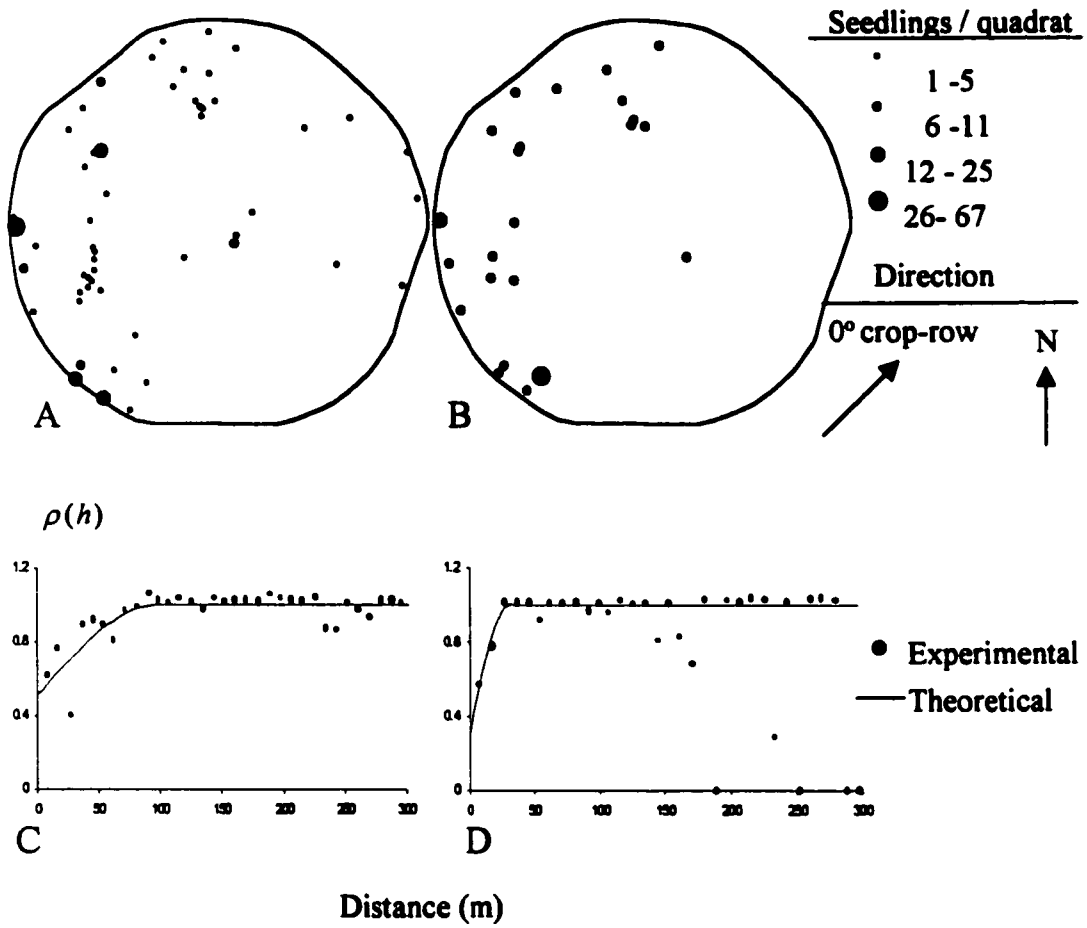

Figure 3. Field sandbur distribution in 1997 (A) and 1998 (B) and correlograms in variogram form (C and D) in the direction of the crop row. Parameter values for correlograms given in Table 6.

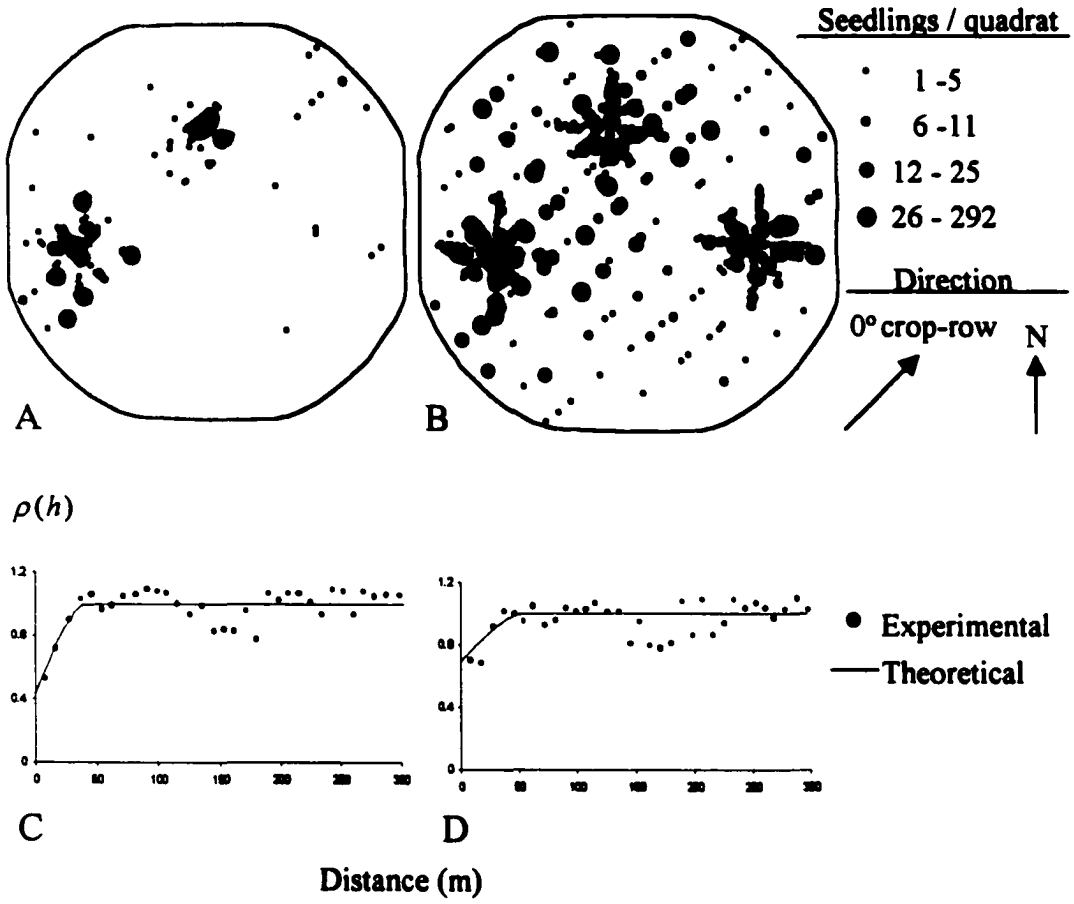

Figure 4. Common lambsquarters (A) and nightshade spp. (B) distribution and correlograms in variogram form (C and D) in the direction of the crop-row (0°) for field 2 in 1998 before a postemergence herbicide application. Parameter values for correlograms given in Table 6.

CHAPTER 2

Spatial Distribution of Plant-Parasitic Nematodes and Correlation with Soil Attributes in Corn Fields

ABSTRACT

Two center pivot irrigated corn (*Zea mays* L.) fields in eastern Colorado were sampled in 1997 and 1998 to develop sampling programs used to map the spatial distribution of plant-parasitic nematode densities within fields. There were 86 to 122 sampling sites taken every 76.2 m on a square grid within both fields. Spiral (*Helicotylenchus* spp.), stunt (*Tylenchorhynchus capitatus*), and lesion (*Pratylenchus neglectus*) plant-parasitic nematodes were detected in both fields in both years. Plant-parasitic nematode mean densities across both years ranged from 20.2 to 53.3 nematodes per 100 g sub-sample in field 1, and 21.0 to 136.4 nematodes per 100 g sub-sample in field 2. In particular, stunt nematode densities significantly ($P \leq 0.05$) increased from 1997 to 1998 in both fields and were greater in field 1 than field 2. It was determined that 23 to 64% of the sampling units were nematode-free for a particular species. Spatial dependence was detected for selected spiral and lesion nematode samples (a collection of sampling units for a particular nematode species within a field and year). Correlogram analysis suggested that 45 to 71% of the variation in density was due to spatial dependence over a geographic distance up to 97 to 845 m for directions of 0, 45, 90, and 135 degrees from the crop row. The lack of detectable spatial dependence for 9 of the 12 samples with the employed sampling method suggests nematode densities in eastern Colorado corn fields are not correlated at separation distances at or greater than 76.2 m and interpolated maps based on grid sampling at these scales should not be used because knowing a nematode density at one field location would not provide any information about the nematode density at an unsampled location. Spiral and stunt nematodes in both fields were correlated with each other over time, suggesting nematode infestations may be consistent over time when corn

is planted in consecutive years. Spiral nematode densities in field 1 in 1997 and 1998 were positively correlated with percent organic matter, silt, and clay, while negatively correlated with percent sand. Significant correlation coefficient values between nematode densities and soil attributes ranged from –0.56 to 0.56. In field 2, the spiral nematode densities were positively correlated with sand and negatively correlated with clay during 1997 while in 1998 the spiral nematode densities were positively correlated with silt. Stunt nematode densities were positively correlated with sand, while negatively correlated with organic matter, silt, and clay in field 2 in 1997. Lesion nematode infestations were not correlated with any soil attribute in either field. Without strong (correlation coefficient values approaching –1 or +1) and / or consistent correlations between soil attributes evaluated in this study and nematode densities, additional soil attributes and corn fields should be evaluated before nematode densities are indirectly estimated. Until more is known about the spatial dependence of plant-parasitic nematode infestations, interpolated distribution maps should be created with caution so as to avoid poor representation of the true infestation in a field and contribute to poor management decisions.

Nomenclature: Corn (*Zea mays* L.); spiral nematode (*Helicotylenchus* spp.); stunt nematode (*Tylenchorhynchus capitatus*); lesion nematode (*Pratylenchus neglectus*)

Keywords: Spatial dependence, spatial structure, geostatistics, sampling, map, plant-parasitic nematode, infestation, organic matter, sand, silt, clay, soil texture, nematode distribution.

INTRODUCTION

Improved sampling procedures are needed to quantify the spatial distribution of plant-parasitic nematode infestations within fields so inputs can be selected and applied to areas that warrant nematode management. Management inputs such as nematicides, cultivation, and planting resistant crop varieties or a less susceptible crop could be implemented in specific nematode-infested areas if the infestations were mapped. The reliability of a nematode distribution map and resulting management recommendations (management map) will depend on the accuracy of estimating nematode densities at unsampled locations.

Plant-parasitic nematodes that inhabit agricultural fields feed on crop roots and can decrease yields (Todd and Oakley 1996). When infestations are heavy, producers are often advised to (1) treat infested fields with a nematicide which is expensive and can promote resistance, (2) grow a resistant crop variety, (3) rotate to a less susceptible crop or (4) quarantine the field (Akhtar 1997). To minimize management costs and reduce the use of nematicides, growers are interested in treating isolated field areas or nematode patches (Evans et al. 1999). The aggregated distribution of plant-parasitic nematodes may be due to the spatial heterogeneity of field attributes and management strategies that affect habitat suitability for reproduction, movement, and survival of nematodes. Field characteristics that have documented influence on nematode densities and distributions vertically and horizontally over time in a soil profile include soil texture (Georgis and Poinar 1983; Koenning et al. 1996; Queneherve 1988), soil nutrients (Francl 1993; Marshela et al. 1992), and soil moisture (Gorres et al. 1998). In addition, external factors such as crop rotation (Howard et al. 1998; Johnson et al. 1975), management inputs

(Brodie 1993; Johnson et al. 1975), crop row spacing (Ferris and Ferris 1974), and plant physiology (Yeates 1987) can impact nematode infestations. Knowing whether certain field attributes correlate with plant-parasitic nematode infestations in a field may assist the future development of optimal sampling programs for map generation.

The aggregated distribution of plant-parasitic nematode infestations has been described using frequency distributions such as the negative binomial (Anscombe 1950; Boag et al. 1996; Goodell and Ferris 1980) and Taylor's Power Law (Boag et al. 1996; Boag and Topham 1984; Ferris et al. 1990). In addition, sampling programs based on the negative binomial and Taylor's Power Law (Taylor 1961) have been employed to estimate mean nematode densities for a field (Boag et al. 1987; Boag and Topham 1984; Ferris et al. 1990; Ferris 1984; McSorley 1982). These methods only infer spatial relationships from the variance in density, while the relative location of sample units is not considered. An alternate approach for the characterization of spatially variable ecological data, such as nematode populations, is geostatistical analysis.

Geostatistical techniques are a way to quantify and model spatial dependence and map (Isaaks and Srivastava 1989) nematode densities. Interpolated density maps can be used to identify areas that need a management input, apply management inputs, and direct future sampling. In particular, geostatistical functions such as correlation, covariance, and semivariance have been used to describe spatial distributions of plant-parasitic nematode densities (Boag et al. 1996; Evans et al. 1999; Gorres et al. 1998; Marshall et al. 1998; Robertson and Freckman 1995; Rossi et al. 1996; Wallace and Hawkins 1994; Webster and Boag 1992). These three functions use the value and location of each sampling unit to summarize the spatial dependence among points at

various distances and directions within a field for a sample. When a phenomenon, such as a nematode infestation, exhibits spatial dependence, the value at one location and the values at other locations are correlated as a function of incremental distance (Rossi et al. 1992; Weisz et al. 1995). Knowing more about the spatial distribution of nematode infestations will assist in determining if interpolated nematode maps can be created for site-specific management and the development of optimal sampling programs needed to map distribution.

A sampling program to estimate a pest infestation is a procedure that specifies how to collect information for an attribute at a particular time from a sampling unit placed at multiple locations within a field (Pedigo 1994). The accuracy of the sampling program must be balanced against the cost of gathering information for grower adoption (Buntin 1994). Soil inhabiting nematodes cannot be identified and counted until they have been extracted from the soil and observed under a microscope. Thus, the time and effort to take samples, extract, kill, count, and identify nematodes can be considerable (Todd 1998). The cost of sampling and estimating nematode densities (10 dollars per sample) (Todd 1998) limits the number of observations that can be taken to produce a distribution map economically.

The purpose of this work was to investigate plant-parasitic nematode spatial dependence, and nematode relationship between years with each other and with soil organic matter, sand, silt, and clay in two corn fields over time to facilitate the future design of optimal sampling programs for creating reliable distribution maps that could be used for site-specific management.

MATERIALS AND METHODS

Field sites. Two grower-managed center-pivot irrigated corn fields (71 and 53 ha) located in Morgan County near Wiggins, Colorado was sampled in 1997 and 1998. Soils present on both pivots include a Valentine sand (sandy, mixed nonacid, mesic Typic Ustipsamment), a Bijou loamy sand (coarse loamy, mixed, mesic Mollic Haplargid), and a Truckton loamy sand (coarse loamy, mixed, mesic Udic Argiustoll). The crop rotation for field 1 was corn (*Zea mays* L.) in 1993, corn (northwest half [crop rows were orientated in a northeast to southwest direction] and northeast quarter) and onions (*Allium cepa* L.) (southeast quarter) in 1994, corn in 1995, sugar beet (*Beta vulgaris* L.) in 1996, and corn in 1997 and 1998. Crop rotation in field 2 was sugar beet (northwest half) and pinto bean (*Phaseolus vulgaris*) (southeast half) in 1993, corn in 1994 and 1995, sugar beet in 1996 and corn in 1997 and 1998. Mean corn yields in 1997 were 10.9 and 13.0 t ha^{-1} for fields 1 and 2, respectively. Fields were not treated with a nematicide during 1997 or 1998.

Nematode sampling. A 76.2 m square grid was established across entire field areas with 122 (field 1) and 91 (field 2) sampling sites (locations where sampling units were placed) during 1997. During 1998, 121 (field 1) and 86 (field 2) sampling sites were established. For both years, sampling sites were spaced 76.2 m apart. All sampling sites were established within the crop rows and referenced with an OmniSTAR 7000[1] differential global positioning system. Plant-parasitic nematodes were sampled less than one week after corn harvest. In 1997, field 1 was sampled on October 27 and field 2 on October 6, while in 1998, field 1 was sampled on November 9 and field 2 on November 17. At each

sampling site, a soil core (sampling unit) 5 cm in diameter by 10 cm deep was taken in the crop row next to a corn plant. The data was transformed by taking the square root and then analyzed using Proc Mixed analysis of variance (SAS 1988) to evaluate differences in mean densities for each nematode species by field, sampling time, and year. Proc Mixed is a robust procedure for nonrandom sampling and nonnormal distributions. All tests were evaluated at $P \leq 0.05$.

Nematodes were extracted from a 100 g sub-sample of soil then counted by species. For the remainder of the paper all nematode densities will be represented based on a sub-sample of 100 g. Kansas State University Plant Nematology Laboratory conducted nematode isolation and identification. The Kansas State University Plant Nematology Laboratory procedure for isolating nematodes, based on methodology established by Christie (1951), from soil particles was conducted by the following method. A 100 g sub-sample of soil was placed into a 1 L graduated cylinder filled with tap water, covered with parafilm, inverted to mix, and settled for 60 sec. Next the mixture was decanted over a 25 mesh screen and then over a 325 mesh screen. Each meshed screen was washed with water into a 150 ml beaker and contents were poured into a 50 ml round bottom centrifuge tube. Tubes were centrifuged at 400xg for 5 min and the solution was decanted from the tubes and 454 g sucrose / L water solution was added to centrifuge tubes and mixed. Tubes than were centrifuged at 400xg for 1 min then the solution was poured over a 325 mesh screen into a 50 ml beaker. To rinse the screen, less than 20 ml of water tap was used. Each beaker than was covered with parafilm and stored a 4C until nematodes were identified and counted under a dissecting microscope (samples can be stored for several weeks).

Soil sampling. Soil organic matter, sand, silt, and clay were sampled before crop planting in 1997 (Fleming et al. 1999). A square grid of 76.2 m was established within each field then within each grid cell a sampling site was established. At each site, a 5.1 cm diameter by 31 cm deep soil core was taken and analyzed for soil organic matter and texture. Individual sampling sites for nematodes and soil attributes did not coincide but sampling sites for nematodes and soil attributes did represent the same field area (a 5806 m^2 square area).

Geostatistic analysis. The spatial distribution of each plant-parasitic nematode species per sample (a collection of sampling units for a particular nematode species, within a field, at a particular sampling time, and year) was quantified by examining the spatial dependence of each infestation with spatial correlograms. A spatial correlogram is a plot of correlation coefficient values for sampling units (nematode density) separated by various geographic distances (lags) and in a particular direction. Correlogram functions ($\rho(h)$) may be a better tool to quantify spatial dependence than variograms ($\gamma(h)$) because correlogram functions filter out local mean and variance trend effects that may occur over the sampling space (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). A correlogram value can only vary from +1 to −1 depending upon whether the correlation between sampling units is positive or negative (Rossi et al. 1992). Correlograms, unlike variograms, tend to have large values at short distances (h) and small values at longer h (Isaaks and Srivastava 1989; Liehold et al. 1993; Rossi et al. 1992). Spatial correlograms were calculated with the following equation:

$$\rho(h) = \frac{1}{N(h)} \sum_{(i,j)|h_{ij}=h} (v_i * v_j - m_{(-h)} * m_{(+h)}) / \sigma_{(-h)}\sigma_{(+h)} \qquad (1)$$

where the tail mean $m_{(-h)}$ is given by:

$$m_{(-h)} = \frac{1}{N(h)} \sum_{i|h_{ij}=h} v_i \qquad (2)$$

and the head mean $m_{(+h)}$ is given by:

$$m_{(+h)} = \frac{1}{N(h)} \sum_{j|h_{ij}=h} v_j \qquad (3)$$

where N(h) is the number of pairs of points separated by h, h is the separation vector, v_i is the sample value at location i, v_j is the sample value at location j which is separated from location i by the vector h, and $\sigma_{(-h)}$ is the lag standard deviation of v_i, and $\sigma_{(+h)}$ is the lag standard deviation of v_j (Isaaks and Srivastava 1989). The $m_{(-h)}$ is the mean of the data values whose locations is –h away from some other data location and $m_{(+h)}$ is the mean of all data values whose locations are +h away from some other data location. For ease of interpretation, each correlogram was converted to variogram form (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995) by subtracting the correlation function from one, as demonstrated by the following equation:

$$\gamma(h) = 1.0 - \frac{1}{N(h)} \sum_{(i,j)|h_{ij}=h} (v_i * v_j - m_{(-h)} * m_{(+h)}) / \sigma_{(-h)}\sigma_{(+h)} \qquad (4)$$

After transforming each correlogram to variogram form, coefficients values tend to be small at short h and large at longer h (Isaaks and Srivastava 1989; Liehold et al. 1993; Rossi et al. 1992). For the remainder of the paper, the plots of the correlogram function in variogram form will be represented as ρ(h).

Important features of the correlogram in variogram form include the nugget, sill, and range (Isaaks and Srivastava 1989). The spatial discontinuity at distance 0 m is the nugget (Rossi et al. 1992). A non-zero nugget represents micro-scale variation below the sampling scale and experimental or measurement error (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). The value at which the plotted points or individual coefficient values plateau is the sill (Rossi et al. 1992). When the correlation coefficient values of the transformed correlogram are plotted as a function of distance, the sill will be equal to one (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). The distance at which the correlation values level off to an asymptote or the sill is known as the range, which defines the maximum distance that sampling units remain correlated spatially (Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). The difference between the sill and nugget represents the proportion of total variation that is due to spatial dependence with the implemented sampling program (Rossi et al. 1992).

Spatial dependence for each sample was analyzed at a total of four horizontal directions of 0, 45, 90, and 135 degrees from the crop rows. The angle of zero degrees was defined as the crop row for each field. Lag increment was set at 80 m and the minimum number of paired sampling units at each lag was set to 30 to ensure an accurate estimate of variation (Journel and Huijbregts 1978; Liebhold et al. 1993; Rossi et al. 1992). In addition, each sample correlogram in variogram form was weighted by the number of pairs per lag. All spatial analysis was conducted using SAGE95[2] geostatistical software. SAGE95 software is able to calculate multiple directional sample correlograms in variogram form and simultaneously model the experimental correlogram. All

correlogram coefficients for the four investigated directions within a sample were simultaneously considered to estimate one nugget (spatial variation below the minimum distance between sampling sites, or experimental or measurement error for a sample) and a range for each direction. Each directional correlogram in variogram form was jointly fit with a spherical model for each direction and best fit was determined by least squares.

Correlation analysis. Inverse distance weighted soil attribute maps were created using ArcView[3] software. In this analysis, twelve nearest neighbors (sampling units) were used to determine each interpolated value with distance power set at two (Gotway et al. 1996). The power of two is commonly selected to limit the influence of distant sampling units on the interpolated value (Gotway et al. 1996). Then a data set containing interpolated soil attribute values that corresponded to each nematode sampling unit was created. Nonparametric Spearman rank correlation coefficients (r_s) (Rees 1989) were calculated as a measure of correlation between nematode densities between years and nematode infestations with soil attributes (soil organic matter, clay, silt, and sand content) because the nematode infestations were not normally distributed.

RESULTS AND DISCUSSION

Nematode infestation. Spiral, stunt, and lesion plant-parasitic nematodes were observed in both fields in both years (Table 1, and Figures 1 and 2). Each species is commonly found in corn production (Windham and Edwards 1999) in Colorado. Stunt and spiral nematodes are common ectoparasites, spending their life cycle outside the host and feed by inserting a stylet into root tissue (Windham and Edwards 1999). Lesion nematodes,

which are migratory endoparasites, are directly associated with corn roots because individuals migrate from the soil matrix to and throughout the root tissue (Windham and Edwards 1999). Feeding by all three species of nematodes likely contributes to root injury, promotes infection by root pathogens, and contributes to yield loss (Khan 1993).

Plant-parasitic nematode mean densities across both years ranged from 20.2 to 53.3 nematodes per sub-sample in field 1, and 21.0 to 136.4 nematodes per sub-sample in field 2 (Table 1). For each sample, the standard deviation was greater than the mean (Table 1), indicating large variation in nematode density among sub-samples. Individual species of nematodes were unlikely to contribute to a significant yield loss in either field because mean densities were low. Densities for lesion and stunt nematodes were below the economic threshold, the infestation density at which yield loss becomes great enough to warrant a management response (Todd and Jardine 1993), in both fields and years. The economic threshold for lesion nematodes in Kansas's corn production is 200 nematodes per 100 g soil (Todd and Jardine 1993), while densities of lesion nematodes in field 1 were 20 (1997) and 28 (1998) nematodes per 100 g soil and in field 2 were 22 (1997) and 21 (1998) nematodes per 100 g soil. The economic threshold for stunt nematodes in Kansas has been set at 500 nematodes per 100 g soil (Todd and Jardine 1993), while stunt nematode densities in field 1 were 26 (1997) and 53 (1998) and in field 2 were 57 (1997) and 136 (1998). For species of spiral nematodes, economic thresholds are usually not established because extremely high numbers of these species are required to demonstrate crop injury (Windham and Edwards 1999). Even though spiral nematodes are usually not considered a primarily pest of corn, they can contribute to overall crop damage (Windham and Edwards 1999).

Stunt nematode densities significantly increased ($P \leq 0.05$) from 1997 to 1998 in both fields and were greater in field 1 than field 2. In particular, the mean density of stunt nematodes was at least two times greater in 1998 than in 1997 in both fields (Table 1). As the mean density of stunt nematodes increased from 1997 to 1998 in both fields, so did the number of sub-samples that had a nematode present. Between 1997 and 1998 in field 1, there was a 22% (64% to 42%) decrease in sub-samples that were stunt nematode-free, and in field 2 there was a 14% (44% to 30%) decrease in sub-samples that were stunt nematode-free (Table 1). The increase in stunt nematode mean densities and infested area over time may be attributed to consecutive corn planting in 1997 and 1998. In a study that investigated *Pratylenchus scribneri* and *Belonolaimus* spp. in a cropping regime of corn and alfalfa (*Medicago sativa* L.), nematode infestations increased when plots were planted to corn (Todd 1991). Todd (1991) suggests the increase in nematode densities within corn plots was due to favorable environments that corn plants supplied for *Pratylenchus scribneri* and *Belonolaimus* sp. reproduction.

However, spiral densities did not significantly increase from 1997 to1998 in both fields, but spiral nematodes were significantly ($P \leq 0.05$) greater in field 2 than in field 1 in both years. Lesion nematode densities did not significantly differ between fields or years. Among the three species, lesion nematodes were less abundant in sub-samples in both years and fields. For example, the mean density of lesion nematodes in field 2 was four times (1997) and five times (1998) less than spiral nematodes, and two times (1997) and six times (1998) less than stunt nematodes.

Spatial dependence. Spatial dependence (nematode densities at one location were correlated as a function of incremental distance and direction to nematode densities at

other locations) was detected for only a few nematode samples with our sampling plan and statistical method. Spatial dependence was detected for lesion nematodes in field 1 during 1997 while spiral nematode densities were spatially related to one another in field 1 during 1998 and in field 2 during 1997.

For spiral nematodes in field 1 during 1998, 71% (nugget of 0.29) of the variation in density was due to spatial dependence over a distance up to 97 to 269 m for the four directions observed in this study (Table 2). In the direction of the crop row the range was 97 m, however at 90 degrees from the crop row, spiral nematode densities were related (Figure 3) at a range of 269 m (Table 2). The spiral nematode sample in field 2 during 1997 had a nugget of 0.55, and 45% of the variation in density was due to spatial dependence over a distance up to 191 to 845 m for the four directions observed in this study (Table 2). In the direction of the crop row spiral nematode densities were related at a range of 279 m (Figure 3). For the lesion nematode sample in field 1 during 1997, 71% (nugget of 0.29) of the variation in density was due to spatial dependence up to 132 to 154 m for the four directions observed in this study (Table 2). In particular, spiral nematode densities were related at a range of 133 m in the direction of the crop row (Figure 3). Results of this study suggest that some sampling units should be observed closer together than 97 m (smallest detected range) for sampling species of lesion and spiral nematodes to create an interpolated map.

Nine out of 12 samples exhibited a pure nugget effect, which occurs when observation pairs separated at various lags (distances) have similar levels of correlation. For mapping purposes, knowing a nematode density at one field location for a sample with a pure nugget effect would not provide any information about the nematode density

at an unsampled location. Thus, a less than reliable interpolated map may be created for 9 of the 12 samples. An unreliable distribution map may lead a producer to make poor management choices. An alternative management choice may be to estimate a mean density and use a non-interpolative method (Roberts et al. 1993), such as posting maps to either apply a uniform input or select areas that should be managed or sampled more intensely.

Pure or large nugget effects can be caused by observing sample units at the wrong scale (the smallest distance between sampling units was too large to capture spatial nematode correlation), using a sampling procedure with high experimental error (Isaaks and Srivastava 1989; Weisz et al. 1995), or a truly random infestation (Isaaks and Srivastava 1989). The number and placement of sample units implemented to evaluate spatial dependence was constrained by the limited amount of time, resources, and multiple goals of this large multidisciplinary research project (Heermann et al. 1999).

In addition to the previously mentioned constraints, other than the study by Robertson and Freckman (1995), the spatial dependence of plant-parasitic nematodes in corn fields has not been thoroughly investigated; thus it was not possible to define a minimum separation distance for sampling prior to the study. Due to these constraints, there probably were an insufficient number of sampling units separated at distances less than 76.2 m apart to detect spatial dependence for many of the nematode infestations. The aggregated distribution of plant-parasitic nematodes in corn fields may occur on a smaller scale due to field characteristics (levels of elevation and soil nutrients)and management strategies (type and timing of inputs) that affect habitat suitability for reproduction, movement, and survival of nematode infestations. Further research to

assess whether spatial dependence exists for plant-parasitic nematode infestations in corn fields, some sample units should be separated at distances less than 76.2 m. In addition, Webster and Boag (1992) suggested nested sampling may be better than grid sampling to discover the spatial scale within which nematodes vary. Their nested sampling procedure first consisted of establishing a 50 m square grid, then establishing an additional observation 16.7 m away from each grid intersection in a random direction. From each of these two points, subsequent observations were established at a distance of 5.6 m in a random direction; this procedure was then repeated for distances of 1.8 m, 0.6 m, 0.2 m, and 0.07 m. Nested sampling may provide more information on the spatial relationship of nematode densities at finer scales without increasing the total number of observations. With the nested sampling method, Webster and Boag (1992) determined that cereal cyst nematodes were spatially dependent within distances of 5 to 50 m.

Additional studies that have investigated the spatial dependence of plant-parasitic nematodes indicated spatial dependence occurred up to a distance (range) of 1 to 10 m in old fields and forest landscapes (Gorres et al. 1998), to 160 m in a reed canary-grass field (Wallace and Hawkins 1994), to 67 m in a sugarcane crop (Rossi et al. 1996), 5 cm to 50 m in a permanent pasture (Marshall et al. 1998), and no spatial dependence was detected in a corn crop (Robertson and Freckman 1995). Robertson and Freckman's (1995) study is the only research that has investigated the spatial autocorrelation of plant-parasitic nematode densities in corn production. They determined plant-parasitic nematode densities were not spatially related in a 48 ha corn field even when distances between paired sampling units ranged from 0.9 to 1200 m. However, for nematodes of bacterivorous, ominvorous, and fungivorous trophic groups, 70 to 99% of the variation in

the sample infestation was due to spatial dependence over the geographic range of 6 to 80 m. They suggest that the lack of spatial dependence of plant-parasitic nematodes may be primarily due to the dispersal nature of these nematodes throughout the growing season. For example, plant-parasitic nematode densities within the crop row change over a growing season, with maximum infestation densities in close proximity to crop roots during active plant and root growth (Dropkin 1980). Because soil samples in Robertson and Freckman's (1995) study and soil samples in the current study were extracted after the crop was actively growing, plant-parasitic nematodes may have migrated from the crop rows and dispersed through the soil profile. To detect the spatial dependence of plant-parasitic nematodes in corn, future sampling may need to be conducted before root maturity.

Nematode correlation between years. Results of Spearman rank correlation analysis shows the densities of spiral nematodes were significantly correlated between years in field 1 (correlation coefficient of 0.53 ($P \leq 0.05$)), while the densities of stunt nematodes over years were significantly correlated in field 1 (correlation coefficient of 0.20 ($P \leq 0.05$)) and field 2 (correlation coefficient of 0.29 ($P \leq 0.05$)). These results suggest nematode infestations may be consistent over consecutive years when a field is planted to corn. To determine if nematode distribution maps could be created one year and then used over consecutive years, nematode infestations over multiple years would need to be evaluated.

Nematode correlation with field attributes. If it can be determined that certain soil attributes, such as organic matter, sand, silt, and clay, can indirectly relate to nematode densities and distributions over time, then this information could assist the development of optimal sampling programs for mapping expected nematode infestations. Sampling spatially variable soil attributes that relate to nematode densities and spatial distribution will likely be less expensive than directly sampling a nematode infestation. If sampling cost and effort can be minimized, map accuracy may increase because it is likely samples could be observed at the necessary intensity needed to estimate nematode densities at unsampled locations.

Significant correlation coefficient values between nematode densities and soil attributes ranged from –0.56 to 0.56 (Table 3). Spiral nematode density in field 1 during 1997 and 1998 was positively correlated with percent organic matter, silt, and clay, while negatively correlated with percent sand (Table 3). Thus, spiral nematode densities increased in areas of high areas of organic matter, silt, and clay, while spiral nematode densities decreased in areas of high sand content in both years (Table 3 and Figures 4 and 5). Soil moisture, which is necessary for plant-parasitic nematode mobility, reproduction, and survival (Dropkin 1980; Ferris and Ferris 1974), has been frequently related to soil attributes of increased levels of organic matter, clay, and silt and decreased levels of sand content (Dropkin 1980; Ferris and Ferris 1974). However, in field 2 the spiral nematode infestation was positively correlated with sand and negatively correlated with clay in 1997 (Table 3). During 1998, spiral nematode infestation was only positively correlated with silt in field 2 (Table 3). Stunt nematode infestation was positively correlated with sand, while negatively correlated with organic matter, silt, and clay in field 2 in 1997,

which were opposite results found for spiral nematodes in field 1 in both years (Table 3). Finally, the lesion nematode infestation was not correlated with any soil attribute in either field (Table 3). Without strong (correlation coefficient values approaching −1 or +1) and / or consistent correlations, additional soil attributes and corn fields should be evaluated before nematode densities are indirectly estimated from these soil attributes.

There was little variability in the soil attributes that were evaluated in these two fields. Soil texture for both fields was classified as either sand or loamy-sand. In particular, percent sand ranged from 71.5 to 92.0%, silt ranged from 0.93 to 16.6%, and clay ranged from 4.1 to 15.6% within both fields (Table 4). Organic matter was also low, ranging from less than 1 to 2% in both fields (Table 4). Additional fields with more soil variability may need to be sampled to determine if there is a strong and / or consistent relationships between soil attributes and nematode densities.

Other studies have also evaluated the correlation between soil attributes and nematode densities. For example, soil bulk density and soil moisture were identified as significantly relating with nematode densities at various times of the year for an old field (Gorres et al. 1998). In addition, coarse-textured soils tended to promote reproduction of *Meloidogyne incognita*, whereas *Rotylenchulus reniformis* reproduction was greatest when soil contained moderate levels of clay and silt (Koenning et al. 1996). Also, Noe and Barker (1985) investigated the correlation of three plant-parasitic nematode densities with 26 edaphic variables and found that soil texture was also an useful predictor of nematode densities. Soil nutrient levels and organic matter can also influence nematode densities. Soil attributes such as Mg have been positively correlated with *Heterodera glycines* cyst and egg infestation densities (Francl 1993), and organic matter supported

the highest infestation densities of *Tylenchulus semipenetrans* (Marshela 1992). Before field attributes are sampled to infer the density of either spiral, lesion, or stunt nematodes to create an interpolated map, additional corn fields should be examined.

Spatial information of plant-parasitic nematodes within whole fields may enhance future sampling programs and control strategies as well as suggest possible field attributes that may influence nematode spatial distributions. However, to adequately evaluate at what distances and directions that spatial dependence of plant-parasitic nematode infestations occurs in corn fields or whether the distribution is truly random, future studies should place some sample units at separation distances less than 76.2 m, and sampling should occur during active root growth.

Knowing the spatial dependence of nematodes is important as we set out to identify cost-effective sampling programs that a grower could implement to map the nematode distribution in other fields in eastern Colorado. For now, since spatial dependence was only detected for 3 of a total 12 nematode samples in our study, there is likely not enough information on the spatial relationship of nematode densities to develop sampling programs for map generation for the total nematode infestation in eastern Colorado corn fields. In addition, sampling spiral and lesion nematodes for map generation at the distance where spiral and lesion nematode densities are spatially related would be very costly at this time. For example, analyzing soil samples taken from a 76.2 m grid (100 sampling sites) in field 2 would cost 1,000 dollars (10 dollars per sample). Until more is known about the spatial dependence of plant-parasitic nematode species, interpolated distribution maps should be used with caution so as to avoid poor representation of the true infestation in a field which could contribute to poor

management decisions. In attempt to minimize sampling effort and cost, soil attributes that may directly related to nematode densities were evaluated. This study suggests that nematode densities may correlate with field attributes of soil texture and organic matter, but additional research is needed before these attributes are used to determine nematode densities for creating reliable nematode density maps.

SOURCES OF MATERIAL

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[2]Isaaks & Co. 1995. SAGE95. 205 E. 3rd Ave. Suite 300 San Mateo, CA 94401, USA.

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Table 1. Nematode infestation for fields 1 and 2 in 1997 and 1998.

Field	Species	Nematode density: Mean (Standard deviation)		Median		Maximum		Nematode-free Sub-sample	
		No. nematodes^{-1}						%	
		1997	1998	1997	1998	1997	1998	1997	1998
1	Spiral	35.5 (85.6)	47.3 (65.4)	4.5	21.5	638	309	50	45
	Stunt	26.2 (82.3)	53.3 (7.47)	0.0	19.0	663	383	64	42
	Lesion	20.2 (30.6)	28.3 (32.0)	10.0	20.0	164	148	41	37
	Total	81.9 (136.7)	128.8 (122.0)	42.5	103.5	897	497	17	9
2	Spiral	86.2 (106.8)	110.5 (139.0)	32.0	53.0	420	731	30	23
	Stunt	56.6 (120.5)	136.4 (207.2)	20.0	71.0	951	1543	44	30
	Lesion	21.5 (39.5)	21.0 (29.5)	10.0	10.5	264	119	44	50
	Total	164.2 (177.8)	267.9 (262.5)	98.0	222.5	961	1727	7	3

Note: Minimum density for all samples was zero.

Table 2. Correlograms by direction for nematode infestations in fields 1 and 2 during 1997 and 1998.

Field	Year	Species	Nugget	Range (degrees[a] (clockwise from the crop row))			
				0	45	90	135
				m			
1	1997	Lesion	0.29	133	154	132	152
1	1998	Spiral	0.29	97	123	269	136
2	1997	Spiral	0.55	279	191	845	279

[a]Direction from the crop rows.

Table 3. Spearman rank correlations between nematode densities and soil attributes.

Field	Soil attributes	Spiral		Stunt		Lesion	
		1997	1998	1997	1998	1997	1998
		r_s					
1	Organic matter	0.46*[a]	0.56*	0.04	-0.08	-0.02	0.01
	Sand	-0.42*	-0.47*	0.04	0.12	0.13	-0.03
	Silt	0.30*	0.41*	0.03	-0.05	-0.15	-0.06
	Clay	0.43*	0.44*	-0.11	-0.13	-0.09	0.10
2	Organic matter	-0.18	0.17	-0.45*	-0.18	-0.003	0.10
	Sand	0.28*	-0.20	0.44*	0.15	0.02	-0.08
	Silt	-0.19	0.24*	-0.56*	-0.20	-0.06	-0.04
	Clay	-0.37*	0.12	-0.21*	-0.11	-0.01	0.17

[a](*) Indicates correlation coefficient was significant at $P \leq 0.05$.

Table 4. Soil attributes for fields 1 and 2.

Field	Soil attribute	Mean (Standard deviation)	Minimum	Maximum
		%		
1	Organic matter	1.0 (0.2)	0.7	2.0
	Sand	85.4 (3.5)	76.1	92.0
	Silt	5.6 (1.7)	0.9	10.3
	Clay	9.0 (2.4)	4.1	15.6
2	Organic matter	1.1 (0.1)	0.5	1.5
	Sand	79.9 (4.1)	71.5	92.0
	Silt	10.4 (2.6)	4.3	16.6
	Clay	9.6 (2.1)	5.6	14.6

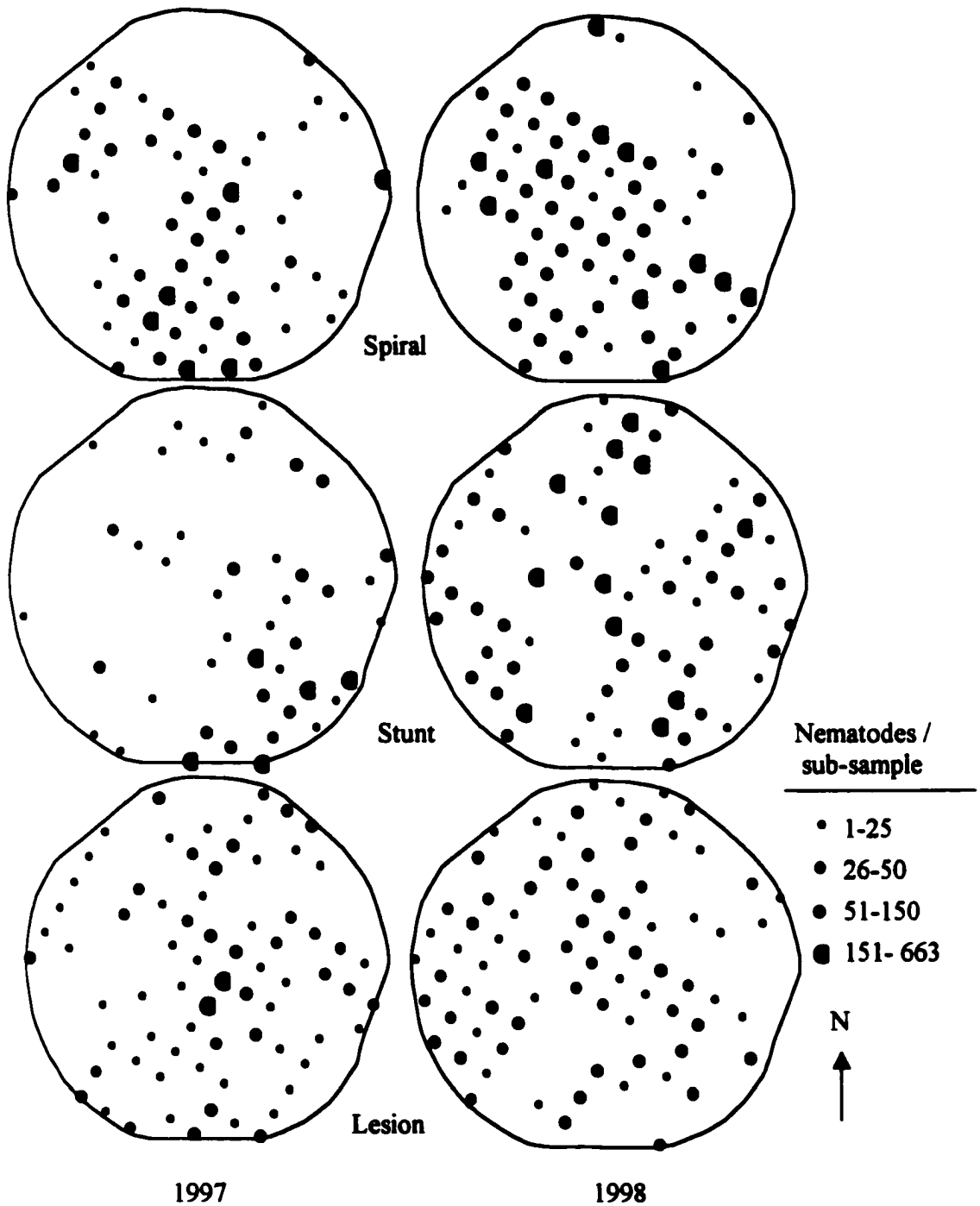

Figure 1. Spiral, stunt, and lesion nematode infestation in 1997 and 1998 in field 1.

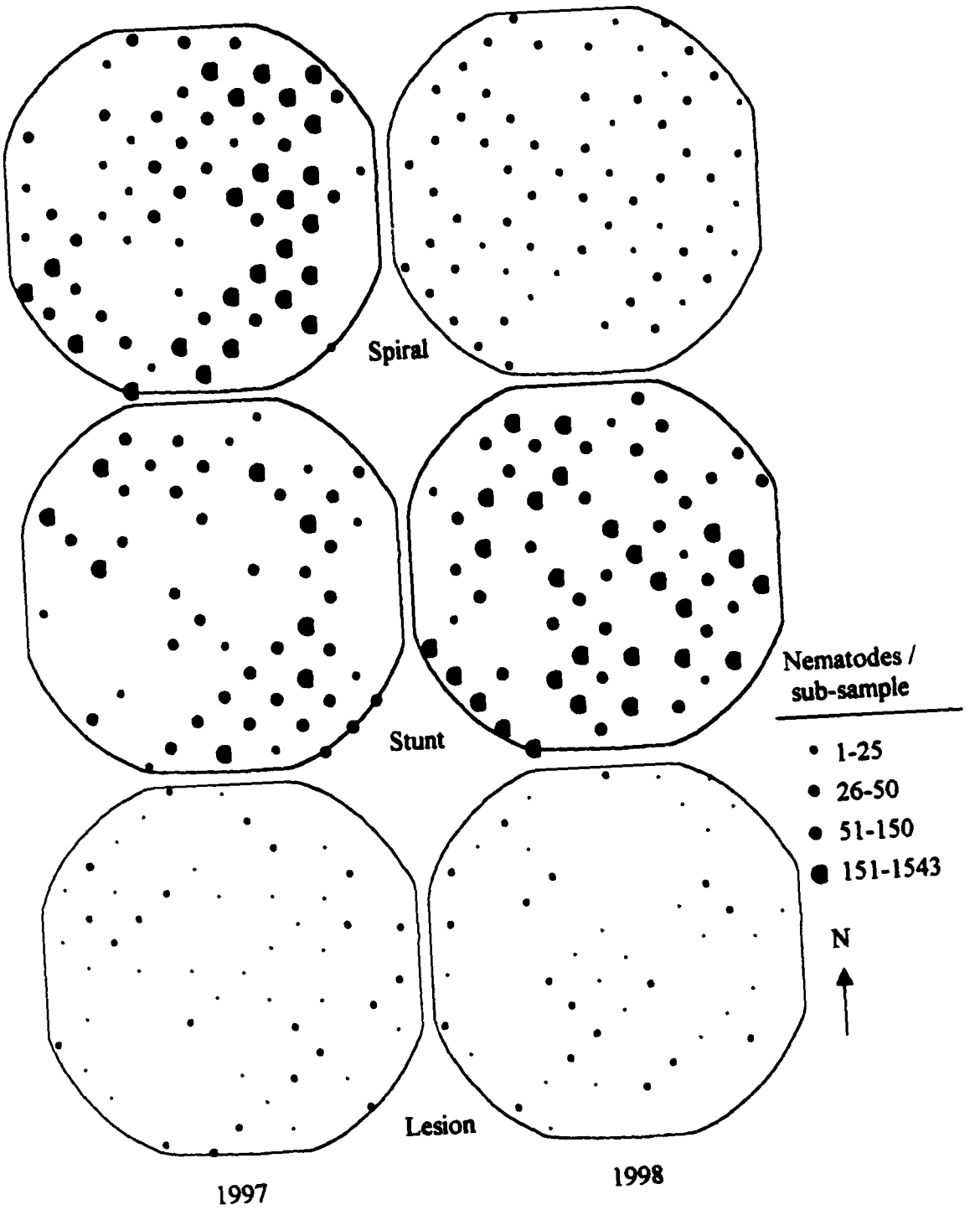

Figure 2. Spiral, stunt, and lesion nematode infestation in1997 and 1998 in field 2.

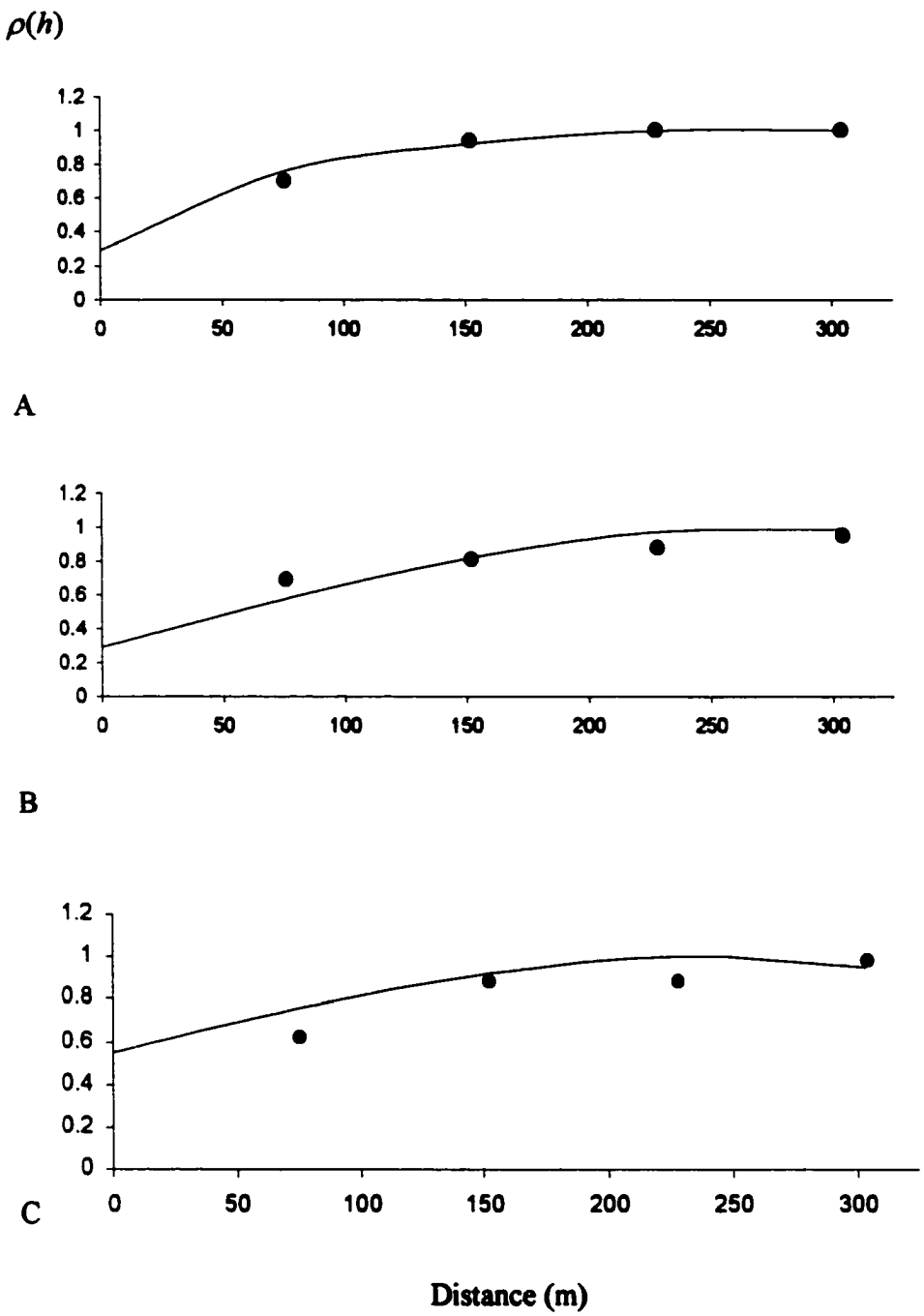

Figure 3. Correlogram in variogram form for lesion nematode in field 1 during 1997 in the direction of the crop row (0 degrees) (A), spiral nematode in field 1 during 1998 perpendicular to the crop row (90 degrees) (B), and spiral nematode in field 2 during 1997 in the direction of the crop row (0 degrees) (C).

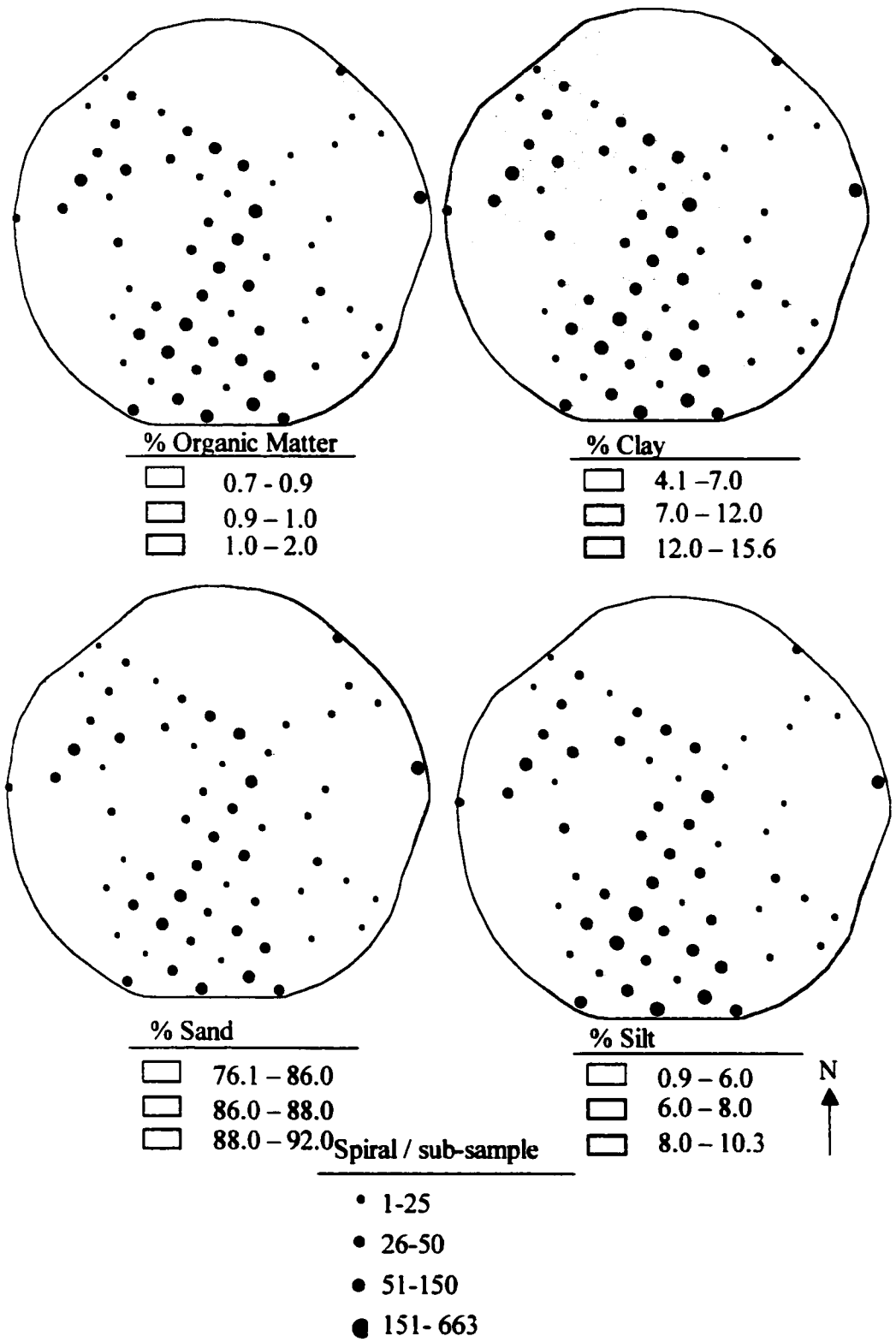

Figure 4. Spiral nematode distribution in field 1 in 1997 with soil organic matter, clay, sand, and silt distributions.

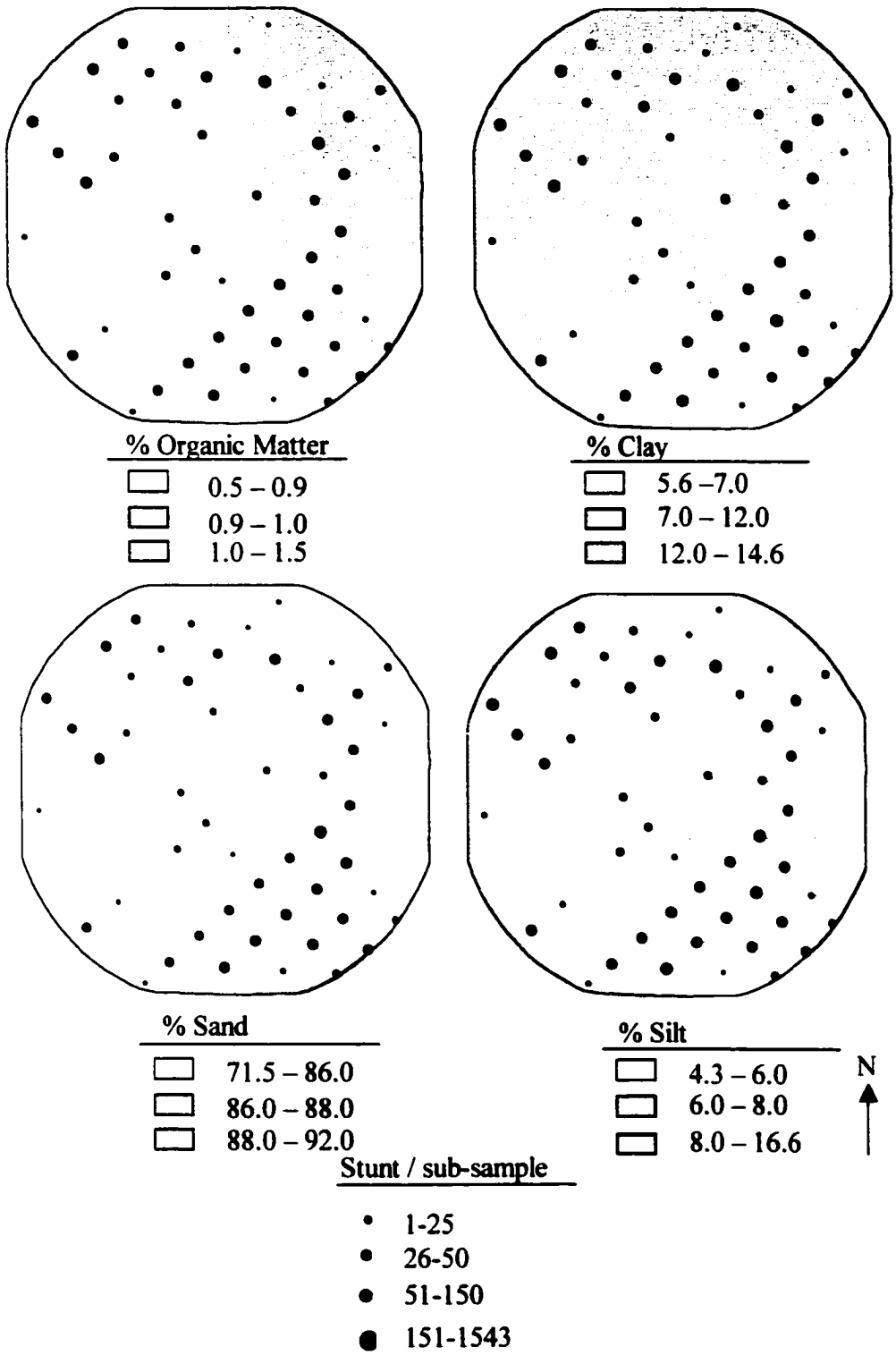

Figure 5. Stunt nematode distribution in field 2 in 1997 with soil organic matter, clay, sand, and silt distributions.

CHAPTER 3

Spatial Distribution of Western Corn Rootworm Eggs and Correlation with Soil Attributes in Corn Fields

ABSTRACT

To develop better sampling plans to estimate the spatial distribution of western rootworm infestations across fields, two center pivot irrigated corn (*Zea mays* L.) fields in eastern Colorado were sampled in 1997 and 1998. There were 86 to 122 sampling sites every 76.2 m on a square grid across both fields. Western corn rootworm eggs were assessed with a 5 cm diameter by 10 cm deep soil core. The mean density of rootworm eggs in field 1 was 0.9 eggs per sub-sample (1997) and 1.7 eggs per sub-sample (1998), while in field 2 the mean densities were 0.5 eggs per sub-sample (1997) and 1.1 eggs per sub-sample (1998). The lack of significant correlations between rootworm egg densities and organic matter, sand, silt, and clay content suggests that these soil properties would be poor indicators of rootworm egg densities in eastern Colorado corn fields. Spatial dependence was only detected in the rootworm egg infestation during 1998 in field 1. Specifically, with a nugget of 0.29, 71% of the variation in the sample egg density was due to spatial dependence over a geographic distance up to 69 m at 0 degrees, 70 m at 45 degrees, 76 m at 90 degrees, and 73 m at 135 degrees from the crop rows. The lack of detectable spatial dependence for 3 of the 4 samples with the employed sampling method suggests rootworm egg densities in eastern Colorado corn fields are not correlated at separation distances at or greater than 76.2 m and interpolated maps based on grid sampling at these scales should not be used because knowing a rootworm egg density at one field location would not provide any information about the rootworm egg density at an unsampled location.

Nomenclature: Corn (*Zea mays* L.); western corn rootworm (*Diabrotica virgifera virgifera* LeConte).

Keywords: Spatial dependence, spatial structure, geostatistics, sampling, map, western corn rootworm eggs, infestation.

INTRODUCTION

Improved sampling procedures are needed to estimate the spatial distribution of western corn rootworm densities within fields to select appropriate inputs and apply them to field areas that warrant rootworm management. If management inputs are going to be selected and applied to certain areas, sampling to create a distribution map of rootworm densities needs to be accurate. The accuracy of a rootworm distribution map and resulting management recommendations will depend on the accuracy of estimating density and spatial arrangement of rootworm infestations. Research emphasis has been on developing sampling programs to estimate a mean density and control recommendations that would be applied across the entire field for beetle (Foster et al. 1986; Hein and Tollefson 1984; Hein et al. 1985; Steffey et al. 1982;Tollefson et al. 1990) and egg infestations (Foster et al. 1979; Hein et al. 1985; Tollefson et al. 1990) with less attention to larval infestations (Stamm et al. 1985).

Western corn rootworm feeding on corn plants can result in a weakened root system or lodging, and is capable of reducing yield by 34.3% in experimental plots (Spike and Tollefson 1991). Western corn rootworm beetles can decrease yields when they feed on silks, thereby interfering with pollination; and larvae feeding on crop roots can decrease yields by disrupting plant physiology (Tollefson and Calvin 1994). However, it is the larval infestation that has the greatest potential to decrease yields and provides the best correlation between estimated rootworm densities and crop yield loss (Tollefson and Calvin 1994). If the need for control can be determined before the corn

crop is planted, a preventive management tactic such as rotation to a nonhost crop may be used rather than applying an insecticide. To manage western corn rootworm infestations producers have relied on (1) cultural techniques (crop rotation, removal of infested ground residue, planting time, tillage, or nitrogen application) to avoid rootworm infestations, (2) preemergence soil insecticides to eliminate larval infestation in the spring, or (3) a post-emergence insecticide to limit beetles from ovipositing in the fall (Brust and King 1994; Stamm et al. 1985; Tollefson and Calvin 1994; Roth et al. 1995; Wright et al. 1997).

To predict the spring larval infestation, either the egg (Hein et al. 1985; Tollefson 1990) or beetle (Stamm et al. 1985; Tollefson 1990) infestation densities are sampled often in the proceeding fall. Sampling the egg and beetle infestations in the fall can be conducted several ways. Egg sampling usually consists of a coring device, spade, or frame (Foster et al. 1979; Tollefson and Calvin 1994) used to evaluate eggs to a depth of 10 to 15 cm, where 80 to 85% of the female beetles oviposit their eggs (Ball 1957; Foster et al. 1979). Beetle sampling to predict next year's infestation of larvae is usually conducted with pheromone traps, visual counts over the whole plant, or in the ear zone from July to early September (Hein and Tollefson 1985; Tollefson and Calvin 1994). Sampling beetle and egg infestations in the fall instead of sampling current larval infestation in the spring allows the farmer time to sample and determine appropriate management strategies (Tollefson and Calvin 1994).

Recommendations have typically been based on less than twenty random sampling units per field (Foster et al. 1979; Steffey et al. 1982; Witkowski et al. 1996) for either egg or beetle infestations, or a prophylactic insecticide treatment is recommended

without field sampling when the field is continuously planted to corn (Witkowski et al. 1996). Observations taken randomly in a field may not adequately estimate the infestation of either egg or beetle densities because both growth stages have an aggregated distribution. The aggregated distribution of eggs and beetles have been inferred from statistical indices such as Geary's C, Moran's I, and Taylor's Power Law (Myers 1978; Steffey and Tollefson 1982)). However, these statistical indices do not directly measure the spatial distribution of rootworms. To quantify the spatial distribution of rootworms, geostatistics techniques can be employed.

Geostatistical techniques are a way to quantify and model spatial dependence and map (Isaaks and Srivastava 1989) rootworm densities. Interpolated density maps can be used to identify areas that need a management input, apply management inputs, and direct future sampling. Geostatistical techniques such as correlation, covariance, and semivariance functions have been used to describe spatial autocorrelation of insect infestations such as *Lygus hesperus* Knight (Schotzko and O'Keeffe 1989) in lentils over the growing season, Colorado potato beetle (*Leptinotarsa decemlineata*), larvae and eggs in five potato fields (Weisz et al. 1995) soil dwelling wireworm (*Limonius californicus*) (Williams et al. 1992). Also, Ellsbury et al. (1998) investigated the spatial dependence of emerging western corn rootworm beetles, and Midgarden et al. (1993) investigated the spatial dependence of western rootworm beetles after emergence. Correlation, covariance, and semivariance functions employed in the above studies use the value and location of each sampling unit in a sample to summarize the spatial dependence among points at various distances and directions across a field (Ellsbury et al. 1998; Midgarden et al. 1993; Schotzko and O'Keeffe 1989; Weisz et al. 1995; Williams et al. 1992). When

a value at one location and the values at other locations are correlated, the infestation exhibits spatial dependence (Rossi et al. 1992; Weisz et al. 1995).

Determining the spatial dependence of rootworm densities and possible field attributes that correlate with rootworm infestations may improve sampling programs needed to create distribution maps or estimate a mean density. If the distance and direction that western corn rootworm densities are spatially correlated were known, optimal sampling plans used to create accurate distribution maps would need to include some observations at the distance where rootworm densities are similar (Weisz et al. 1995). However, if the objective were to acquire an independent estimate of the mean density, a sampling plan would need to include some observations above the distance where rootworm densities are no longer similar (Weisz et al. 1995).

The accuracy of the sampling program must be balanced against the cost of gathering the information and should reduce the uncertainty involved in decision making. The cost of sampling and estimating western corn rootworm egg densities limits the number of observations that can be collected to produce a distribution map or estimate a mean density. An optimal sampling plan based on the spatial dependence of a rootworm infestation for a particular management system will be important if reliable distribution maps are going to be created and used to assist those who make management decisions and inputs. Determining the spatial arrangement and distribution of a rootworm densities could lead to the development of sampling programs that a scout could implement to create reliable distribution maps or estimate a mean density.

The purpose of this work was to investigate western corn rootworm egg spatial dependence and the relationship of egg densities with soil organic matter, sand, silt, and

clay in two corn fields over time to facilitate the future design of sampling programs for creating reliable distribution maps that could be used for site-specific management.

MATERIALS AND METHODS

Field sites. Two grower-managed center-pivot irrigated corn fields (71 and 53 ha) located in Morgan County near Wiggins, Colorado, were sampled in 1997 and 1998. Soils present on both pivots include a Valentine sand (sandy, mixed nonacid, mesic Typic Ustipsamment), a Bijou loamy sand (coarse loamy, mixed, mesic Mollic Haplargid), and a Truckton loamy sand (coarse loamy, mixed, mesic Udic Argiustoll). The crop rotation for field 1 was corn (*Zea mays* L.) in 1993, corn (northwest half [crop rows were orientated in a northeast to southwest direction] and northeast quarter) and onions (*Allium cepa* L.) (southeast quarter) in 1994, corn in 1995, sugar beet (*Beta vulgaris* L.) in 1996, and corn in 1997 and 1998. Crop rotation in field 2 was sugar beet (northwest half) and pinto bean (*Phaseolus vulgaris*) (southeast half) in 1993, corn in 1994 and 1995, sugar beet in 1996 and corn in 1997 and 1998. Mean corn yields in 1997 were from 10.9 and 13.0 t ha^{-1} for fields 1 and 2, respectively. Fields were not treated with an insecticide to specifically control western corn rootworm eggs in 1997 or 1998. However, during 1997 field 2 was treated with phosphorothioate on July 1 to control grasshoppers, dimethylcyclopropanecarboxylate on August 14 to control European corn borer (*Ostrinia nubilalis*), and dimethoate on August 26 to control mite infestations. Then in 1998, field 2 was treated with dimethylcyclopropanecarboxylate on August 14 to control European corn borer. Even though these insecticides were applied to control grasshoppers,

European corn borer, or mite infestations, the insecticides also had activity on rootworm infestations.

Western corn rootworm egg sampling. A 76.2 m square grid was established across entire field areas, with 122 (field 1) and 91 (field 2) sampling sites (locations where sampling units were placed) during 1997, and 86 (field 1) and 121 (field 2) sampling sites during 1998. Rootworm eggs were sampled at the same sampling sites in each field. All sampling sites were established within the crop rows and referenced with an OmniSTAR 7000[1] differential global positioning system. Western rootworm eggs were sampled less than one week after corn harvest. In 1997 field 1 was sampled on October 27 and field 2 on October 6, and in 1998 field 1 was sampled on November 9 and field 2 on November 17. At each observation a soil core (sampling unit) of 5 cm diameter by 10 cm deep was taken in the crop row next to a corn plant. The data was transformed by taking the square root and then analyzed using Proc Mixed analysis of variance (SAS 1988) to evaluate differences in rootworm mean densities by field, sampling time, and year. Proc Mixed is a robust procedure for nonrandom sampling and nonnormal distributions. All tests were evaluated at $P \leq 0.05$.

Egg extraction and identification was conducted by French Agricultural Research, Inc. Procedures for isolating rootworm eggs from soil particles were based on methodology established by Matteson (1966). First a 300 g sub-sample of soil was placed in a series of two sieves. The soil and egg mixture was washed through a 20 mesh and a 50 mesh screen . Next the soil-egg mixture collected in the 50 mesh screen was placed into a 1000 ml separatory funnel with a sugar solution at 1.20 to 1.25 specific

gravity. The solution is thoroughly mixed with the soil by physically agitating the separatory funnel on its side then the funnel was slowly returned to the upright position. After the solution was mixed eggs floated to the top of the solution while the soil sank to the bottom of the funnel. The soil and most of the solution was removed from the funnel leaving the floating eggs with some organic debris. Next water was added and the eggs sank to the bottom of the funnel. Eggs plus organic debris were removed and observed under a dissecting microscope for total egg count. For the remainder of the paper, all rootworm egg densities will be represented based on a sub-sample of 300 g.

Soil sampling. Soil organic matter, sand, silt, and clay were sampled before crop planting in 1997 (Fleming et al. 1999). A 76.2 m square grid was established within each field then within each grid cell a sampling site was established. At each site a 5.1 cm diameter by 31 cm deep soil core was taken and analyzed for soil organic matter and texture. Individual sampling sites for rootworms and soil attributes did not coincide but sampling sites for rootworms and soil attributes did represent the same field area (a 5806 m^2 square area).

Geostatistic analysis. The spatial distribution of western corn rootworm eggs per sample (a collection of sampling units, within a field, at a particular sampling time, and year) was quantified by examining the spatial dependence of each infestation with spatial correlograms. A spatial correlogram is a plot of correlation coefficient values for sampling units (rootworm density) that are separated by various geographic distances (lags) and in a particular direction. Correlogram functions ($\rho(h)$) may be a better tool to

quantify spatial dependence than variograms (γ(h)) because correlogram functions filter out local mean and variance trend effects that may occur over the sampling space (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). A correlogram value can only vary from +1 to −1, depending upon whether the correlation between sampling units is positive or negative (Rossi et al. 1992). Correlograms, unlike variograms, tend to have large values at short distances (*h*) and small values at longer *h* (Isaaks and Srivastava 1989; Liehold et al. 1993; Rossi et al. 1992). Spatial correlograms were calculated with the following equation:

$$\rho(h) = \frac{1}{N(h)} \sum_{(i,j)|h_{ij}=h} (v_i * v_j - m_{(-h)} * m_{(+h)}) / \sigma_{(-h)}\sigma_{(+h)} \qquad (1)$$

where the tail mean $m_{(-h)}$ is given by:

$$m_{(-h)} = \frac{1}{N(h)} \sum_{i|h_{ij}=h} v_i \qquad (2)$$

and the head mean $m_{(+h)}$ is given by:

$$m_{(+h)} = \frac{1}{N(h)} \sum_{j|h_{ij}=h} v_j \qquad (3)$$

where N(*h*) is the number of pairs of points separated by *h*, *h* is the separation vector, v_i is the sample value at location *i*, v_j is the sample value at location *j* which is separated from location *i* by the vector *h*, $\sigma_{(-h)}$ is the lag standard deviation of v_i, and $\sigma_{(+h)}$ is the lag standard deviation of v_j (Isaaks and Srivastava 1989). The $m_{(-h)}$ is the mean of the data values whose locations is −h away from some other data location and $m_{(+h)}$ is the mean of all data values whose locations are +h away from some other data location. For ease of interpretation, each correlogram was converted to variogram form (Isaaks and Srivastava

1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995) by subtracting the correlation function from one, as demonstrated by the following equation:

$$\gamma(h) = 1.0 - \frac{1}{N(h)} \sum_{(i,j)|h_{ij}=h} (v_i * v_j - m_{(-h)} * m_{(+h)}) / \sigma_{(-h)} \sigma_{(+h)} \qquad (4)$$

After transforming each correlogram to variogram form, coefficients values tend to be small at short *h* and large at longer *h* (Isaaks and Srivastava 1989; Liehold et al. 1993; Rossi et al. 1992). For the remainder of the paper, the plots of the correlogram function in variogram form will be represented as ρ(h).

Important features of the correlogram in variogram form include the nugget, sill, and range (Isaaks and Srivastava 1989). The spatial discontinuity at distance 0 m is the nugget (Rossi et al. 1992). A non-zero nugget represents micro-scale variation below the sampling scale and experimental or measurement error (Isaaks and Srivastava, 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). The value at which the plotted points or individual coefficient values plateau is the sill (Rossi et al. 1992). When the correlation coefficient values of the correlogram are plotted as a function of distance, the sill will be equal to one (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). The distance at which the correlation values level off to an asymptote or the sill is known as the range, which defines the maximum distance at which sampling units remain correlated spatially (Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). The difference between the sill and nugget represents the proportion of total variance that is due to spatial dependence with the implemented sampling program (Rossi et al. 1992).

Spatial dependence for each sample was analyzed at a total of four horizontal directions of 0, 45, 90, and135 degrees from the crop rows. The angle of zero degrees

was defined along the crop row for each field. Lag increment was set at 80 m and a minimum number of paired sampling units at each lag were set to 30 in order to ensure an accurate estimate of variance (Journel and Huijbregts 1978; Liebhold et al. 1993; Rossi et al. 1992). In addition, each sample correlogram in variogram form was weighted by the number of pairs per lag. All spatial analysis was conducted using SAGE95[2] geostatistical software. SAGE95 software is able to calculate multiple directional sample correlograms in variogram form and simultaneously model the experimental correlogram. All correlogram coefficients for the four investigated directions within a sample were simultaneously considered to estimate one nugget (spatial variation below the minimum distance between sampling sites, or experimental or measurement error for a sample) and a range for each direction. Each directional correlogram in variogram form was jointly fit with a spherical model for each direction and best fit was determined by least squares.

Correlation analysis. Inverse distance weighted soil attribute maps were created using ArcView[3] software. In this analysis, twelve nearest neighbors (sampling units) were used to determine each interpolated value with distance power set at 2 (Gotway et al. 1996). The power of 2 is commonly selected to limit the influence of distant sampling units on the interpolated value (Gotway et al. 1996). Then a data set containing interpolated soil attribute values that corresponded to each rootworm egg sub-sample was created. Nonparametric Spearman rank correlation coefficients (r_s) (Rees 1989) were calculated as a measure of correlation between each rootworm egg densities and soil attributes (soil organic matter, clay, silt, and sand content) because rootworm densities were not distributed normally.

RESULTS AND DISCUSSION

Infestation. Western corn rootworm eggs were detected in both fields (Figure 1). The mean density of rootworm eggs in field 1 during 1997 was 0.9 egg per sub-sample with a standard deviation of 5.7; the mean density increased to 1.7 eggs per sub-sample during 1998 with a standard deviation of 5.0 (Table 1). In field 2, the mean density of rootworm eggs was 0.5 egg per sub-sample during 1997 with a standard deviation of 1.3, and increased to 1.1 egg per sub-sample in 1998 with a standard deviation of 5.8 (Table 1). Even though egg densities increased in both fields from 1997 to 1998, the increase was not significant ($P \leq 0.05$). Maximum egg density for a sub-sample in field 1 was 61 in 1997 and 36 in 1998; in field 2 the maximum egg density per sub-sample was 9 in 1997 and 53 in 1998 (Table 1). In addition to the low mean densities of eggs detected in both fields and years, 48 to 85% of sampling units were rootworm egg-free (Table 1).

Low corn rootworm densities in these fields may be attributed to insecticides that were used to control grasshoppers, European corn borer, and mite infestations in field 2 as well as soils with high sand content (71 to 92%). Soils with high sand content, such as the ones present in both fields (Valentine sand, Bijou loamy sand and a Truckton loamy sand), have limited surface cracking and decreased soil moisture, which may have contributed to less favorable sites for egg oviposition (Brust and House 1990).

Spatial dependence. Spatial dependence (rootworm densities at one location were correlated as a function of incremental distance and direction to rootworm densities at other locations) was only detected for the rootworm egg infestation in field 1 during 1998

(Figure 2). Specifically, with a nugget of 0.29, 71% of the variation in the sample egg density was due to spatial dependence over a geographic distance up to 69 m at 0 degrees, 70 m at 45 degrees, 76 m at 90 degrees, and 73 m at 135 degrees from the crop rows.

As we were unable to detect spatial dependence at a separation distance of 76.2 m for 3 of the 4 samples and a less than reliable interpolated map may be created (Schotzko and O'Keeffe 1989; Weisz et al. 1995). An unreliable distribution map may lead a producer to make poor management choices and applications. An alternative management choice may be to estimate a mean density and use a non-interpolative method (Roberts et al. 1993), such as posting maps to either apply a uniform input or select areas that should be managed or sampled more intensely. Until more is known about the spatial dependence of rootworm densities in eastern Colorado corn fields, interpolated distribution maps should be used with caution so as to avoid poor representation of the true infestation in a field, which could contribute to poor management decisions.

Pure or large nugget effects can be caused by observing sample units on the wrong scale (the smallest distance between sampling units being too large), using a sampling procedure with high experimental error (Isaaks and Srivastava 1989; Weisz et al. 1995), or detecting a infestation with a random distribution (Isaaks and Srivastava 1989). The number and placement of sample units that were implemented to evaluate spatial dependence was constrained by the limited amount of time, resources, and multiple goals of this large multidisciplinary research project (Heermann et al. 1999). Due to these constraints, there probably were an insufficient number of sampling units

separated at distances below 76.2 m to detect spatial dependence for any of the rootworm infestations. Western corn rootworm egg infestations in eastern Colorado corn fields may have a random spatial distribution due to the lack of variability in soil texture (soil texture was classified as sand or sandy-loam) and continual use of pesticides. To adequately assess if the 76.2 m square grid was too large to evaluate spatial dependence for rootworm infestations in these fields, some sample units would need to be placed at shorter separation distances.

Rootworm egg correlation with soil attributes. If it can be determined that there is a relationships between between eggs and field attributes in corn fields over time, the information could be used to develop sampling programs for creating reliable distribution maps. Sampling spatially variable soil attributes that correlate with rootworm egg densities will likely be less expensive than directly sampling a rootworm infestation. If sampling cost and effort can be minimized, map accuracy may increase since it is likely that more samples could be observed at the necessary distances needed to estimate rootworm densities at unsampled locations.

Field attributes such as soil texture, soil moisture, crop residue, nitrogen levels, manure applications, weeds, and irrigation have been shown to influence corn rootworm oviposition, egg development, beetle emergence, and larval survival (Allee and Davis 1996; Brust and House 1990; Johnson et al. 1984; Kirk et al. 1968; Weiss et al. 1983). However, soil attributes that were evaluated in this study did not correlate with rootworm egg densities (Table 2). The lack of significant correlations between rootworm egg densities with organic matter, sand, silt, and clay content suggests that these soil

properties would be poor indicators of rootworm egg densities in eastern Colorado corn fields. The lack of significant correlations between soil attributes and rootworm egg densities may be due to the low egg infestation and the minimal variability of soil attributes that were evaluated in these two fields. Soil texture for both fields was classified as either sand or loamy-sand. In particular, the percentage of sand ranged from 71.5 to 92.0%, silt ranged from 0.93 to 16.6%, and clay ranged from 4.1 to 15.6% within both fields (Table 3).

Results of this study add needed information on the spatial distribution of western corn rootworm egg infestations over time in Colorado corn fields, which is important in the development of future research and sampling plans. For now, there is likely not enough information on the spatial relationship of rootworm densities to develop sampling programs for map generation for the rootworm egg infestation in eastern Colorado corn fields because spatial dependence was only detected for 1 out of 4 rootworm egg samples in our study. Until more is known about the spatial dependence of western corn rootworm densities, interpolated distribution maps should be created with caution so as not to poorly represent the true infestation in a field and make poor management decisions. Alternative management decision aids may be to estimate a mean egg density and create posting maps that can be used to direct future sampling efforts and management treatments.

SOURCES OF MATERIAL

[1]OmniSTAR, Inc, 8200 West glen, Houston, TX 77063, USA.

[2]Isaaks & Co. 1995. SAGE95. 205 E. 3rd Ave. Suite 300 San Mateo, CA 94401, USA.

[3]ArcView GIS. 1996. Environmental Systems Research Institute Inc., Redlands, CA USA.

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Table 1. Western corn rootworm egg summary statistics per field and year.

Field	Year	Rootworm egg density: Mean (Standard deviation)	Median	Maximum	Rootworm egg-free sub-samples
		No. sub-sample^{-1}			%
1	1997	0.9(5.7)	0.0	61	83
	1998	1.7 (5.0)	0.0	36	69
2	1997	0.5(1.3)	0.0	9	78
	1998	1.1 (5.8)	0.0	53	82

Note: Minimum density for all samples was zero.

Table 2. Spearman rank correlations between western corn root worm egg densities and soil attributes.

Field	Soil attribute	Egg	
		1997	1998
		r_s	
1	Organic matter	-0.11	0.12
	Sand	0.15	-0.03
	Silt	-0.04	0.03
	Clay	-0.16	-0.02
2	Organic matter	-0.02	0.15
	Sand	-0.06	-0.10
	Silt	0.02	-0.001
	Clay	0.08	0.14

[a](*) No correlations were significant at $P \leq 0.05$.

Table 3. Soil attribute in fields 1 and 2.

Field	Soil attribute	Mean (Standard deviation)	Minimum	Maximum
		%		
1	Organic matter	1.0 (0.2)	0.7	2.0
	Sand	85.4 (3.5)	76.1	92.0
	Silt	5.6 (1.7)	0.9	10.3
	Clay	9.0 (2.4)	4.1	15.6
2	Organic matter	1.1 (0.1)	0.5	1.5
	Sand	79.9 (4.1)	71.5	92.0
	Silt	10.4 (2.6)	4.3	16.6
	Clay	9.6 (2.1)	4.3	16.6

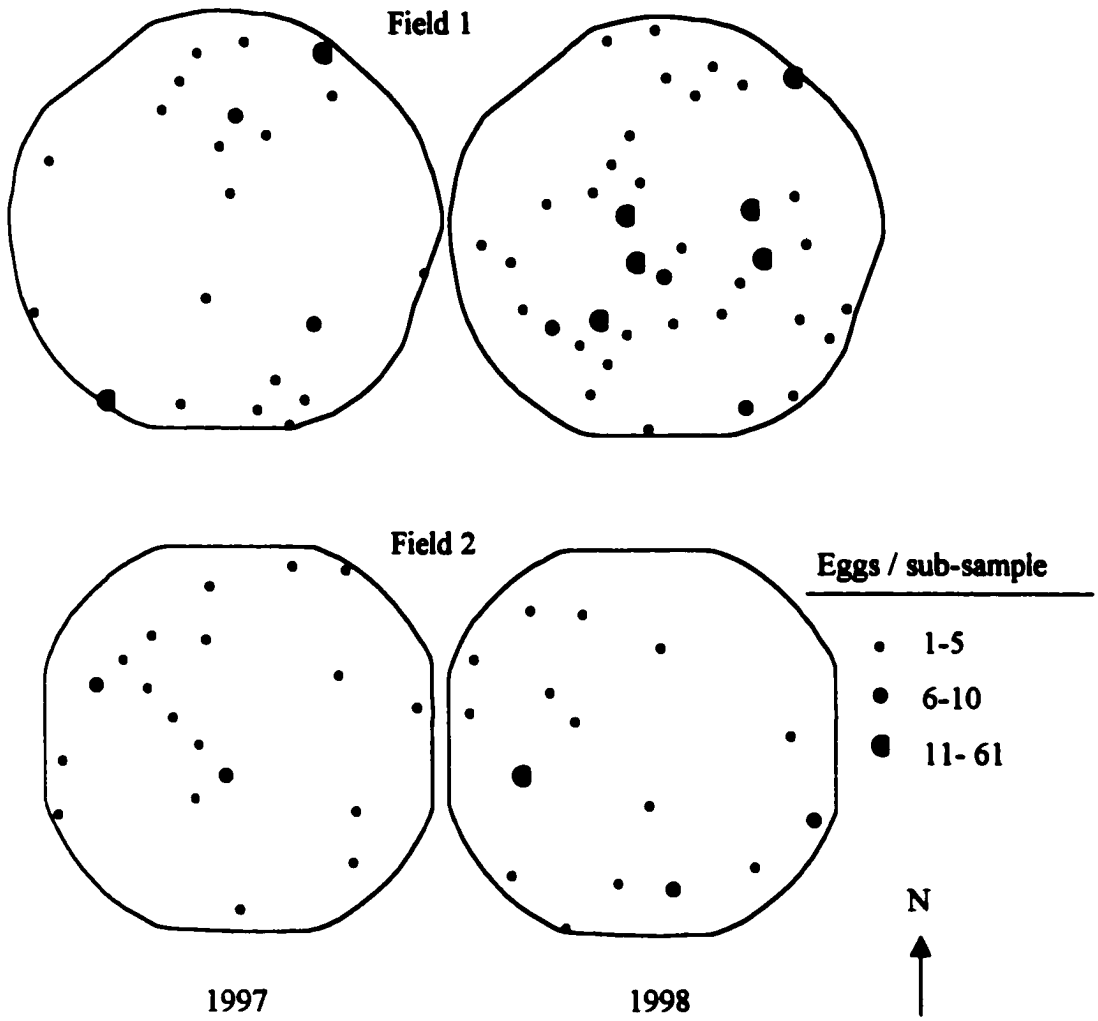

Figure 1. Western corn rootworm egg distribution for fields 1 and field 2 in 1997 and 1998.

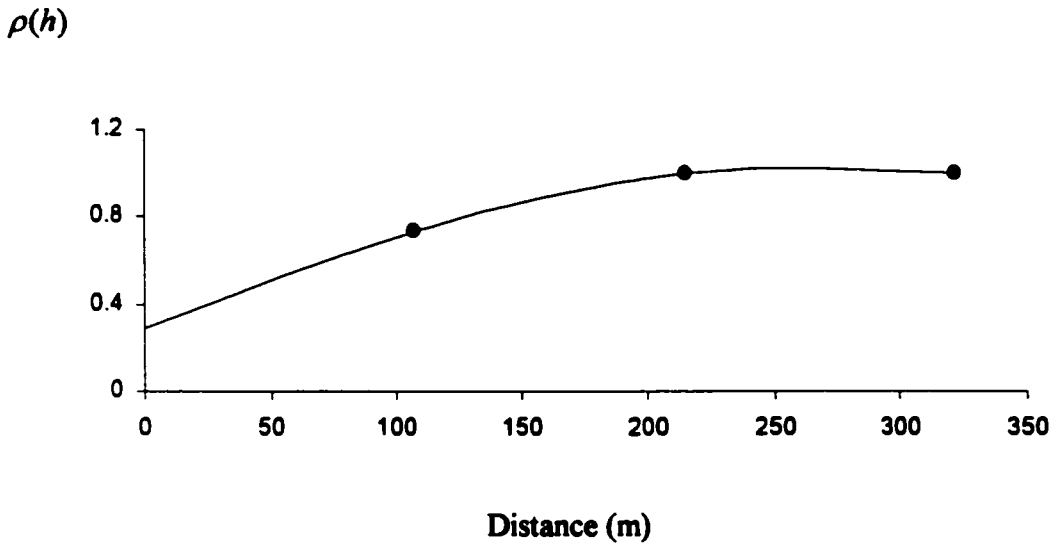

Figure 2. Correlogram in variogram form for rootworm eggs in field 1 during 1998 at 135 degrees from the direction of the crop row.

CHAPTER 4

Spatial Distribution of Triazine Resistant Pigweed Seedbank Populations and Correlation with Soil Attributes in Corn Fields.

ABSTRACT

Weed management could be more efficient if the producer had more accurate, field specific information about the spatial variability of field attributes that promote triazine resistant pigweed populations. If it could be determined that triazine resistant pigweed populations are correlated to a set of soil and landscape attributes, then these attributes could be used to evaluate field areas that promote weed resistance in other fields. In 1997 and 1998, two center pivot irrigated corn fields in eastern Colorado were sampled for pigweed seedlings and seedbank at 536 to 564 sampling sites. During 1997 in field 1, 5% of the soil cores had an atrazine resistant pigweed and 3% of the soil cores for the 1998 sample had an atrazine resistant pigweed. For field 2, all of the pigweed seedlings for the 1997 sample treated with atrazine were killed, but 1% of the soil cores in 1998 had an atrazine resistant pigweed. Pigweed germination ranged from 67 to 76%. Results of Spearman rank correlation analysis shows the distribution of resistant pigweed was significantly correlated between years, suggesting the resistant pigweed population was consistent over time and distribution maps may be used over consecutive years. There was no significant correlation between soil attributes and resistant weed populations in field 2 for both years. However, in field 1 during 1997, triazine resistant pigweed seedbank population was positively correlated with organic matter and clay and negatively correlated with sand, while in 1998 triazine resistant pigweed seedbank population was positively correlated with clay. Clay may be an adequate indicator of atrazine resistant pigweed populations in fields in eastern Colorado.

Nomenclature: Atrazine, (2-chloro-4-ethylamino-6-isopropylamino-s-triazine); pigweed, *Amaranthus* spp. AMAXX; corn, *Zea mays* L. ZEAMX.

Keywords: Pigweed, spatial distribution, resistance, atrazine, seedbank.

INTRODUCTION

Atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine) has played a major role in the achievement of weed control in corn production since its introduction in the late 1950's (Koskinen and Clay 1997). In 1990 alone, 61% of corn fields in Iowa were treated with atrazine, corresponding to an application of approximately 3.4 million kg of atrazine (Hartzler and Wintersteen 1991). The high usage of atrazine and its inherent persistence has contributed to its detection in ground water, limited crop rotation choices, crop injury, and the selection for resistant weeds (Ivany et al. 1985; Koskinen et al. 1990; Stephenson et al. 1990). To enhance weed and crop management practices, it will be important to apply atrazine to specific field areas where atrazine leaching, crop injury, and selection pressure for resistance is minimized.

The most common problem with herbicide residues in soil is excessive persistence (Shea 1985). Persistence of a herbicide should be long enough to give acceptable weed control but not long enough that its residues affect the growth of the following crop (Walker 1987). The availability and thus bioactivity of herbicides in soil is closely associated with adsorption and degradation processes. It is known that such factors as soil properties, microbial activity, weather conditions, and tillage can influence the persistence and degradation of atrazine (Gan et al. 1996; Koskinen and Clay 1997;

Reinhardt and Nel 1993; Walker and Zimdahl 1981). All of these properties can interact and affect the degradation rate of atrazine and hence, its persistence (Walker 1984).

In particular, Reinhardt and Nel (1993) suggested that higher pH and higher adsorptive capacity of clay soils can cause atrazine to persist longer than in loamy sand soils, while Lavy et al. (1973) determined atrazine persistence typically increases with soil pH, soil depth, lower temperatures, and lower soil water content. Clay and organic matter have a greater amount of surface area and exchange sites than sand or silt particles (Koskinen and Clay 1997). As a result, atrazine applied to areas with higher clay or organic matter content may persist for longer periods of time, within the depth of weed germination, than areas with higher sand content. Sand has less surface area and available sites for atrazine sorption, which allows atrazine to move easily through the soil profile (Koskinen and Clay 1997). Soil pH is a likely indicator of atrazine persistence in fields, and resistant weed populations, because soil pH affects atrazine sorption in soil (Koskinen and Clay 1997; Lavy et al. 1973; Reinhardt and Nel 1993). A study by Walker and Zimdahl (1981) determined that the half-life of atrazine in several soils varied from about one month in warm, wet soil (25 C; field capacity soil water) to about one year in cool dry soil (5 C; 25% field capacity soil water). As atrazine use and persistence increases so will the selection pressure for resistant weed biotypes. Atrazine characteristically has a long residual activity in the soil and a single dominant site of action (Eberlein et al. 1992). A single site of action, repeated applications, and long persistence of atrazine in the soil have lead to the development of resistant weed biotypes (Eberlein et al. 1992).

Due to the variability in soil attributes within a field (Frogbrook et al. 1999), atrazine persistence is suspected to vary across a field. If soil and landscape attributes could be identified to promote the development of resistant biotypes, then a producer could manage these high-risk field areas appropriately to reduce selection pressure for resistant weed biotypes. Currently, no study has characterized the soil and field attributes that promote selection pressure for resistant weed biotypes. It was our intent to investigate the spatial distribution of triazine resistant pigweeds within the seedbank. In addition, the relationship between the resistant pigweed population over growing seasons, the relationship of the resistant pigweed seedbank population with the seedling population, and the resistant pigweed seedbank population with soil attributes (pH, soil organic matter, clay, silt, and sand content) were investigated in two corn fields in eastern Colorado to evaluate the potential of reducing weed herbicide-resistance.

MATERIALS AND METHODS

Field sites. Two grower-managed center-pivot irrigated corn fields (71 and 53 ha) located in Morgan County near Wiggins, Colorado were sampled in 1997 and 1998. Soils present on both pivots included a Valentine sand (sandy, mixed nonacid, mesic Typic Ustipsamment), a Bijou loamy sand (coarse loamy, mixed, mesic Mollic Haplargid), and a Truckton loamy sand (coarse loamy, mixed, mesic Udic Argiustoll). The crop rotation for field 1 was corn (*Zea mays* L.) in 1993, corn (northwest half [crop rows were orientated in a northeast to southwest direction] and northeast quarter) and onions (*Allium cepa* L.) (southeast quarter) in 1994, corn in 1995, sugar beet (*Beta vulgaris* L.) in 1996, and corn in 1997 and 1998. Crop rotation in field 2 was sugar beet

(northwest half) and pinto bean (*Phaseolus vulgaris*) (southeast half) in 1993, corn in 1994 and 1995, sugar beet in 1996 and corn in 1997 and 1998. Mean corn yields in 1997 were from 10.9 and 13.0 t ha^{-1} for fields 1 and 2, respectively. Herbicides were selected and applied by each producer (Table 1). Preemergence herbicides were applied in 1997 (Table 1) to remove a winter grass cover crop.

Sampling grids. Weed sampling sites (locations where sampling units were placed) were established within the crop rows on a 76.2 m square grid (Figure 1). In addition, three 23223 m^2 square areas were randomly chosen in each field and 150 sampling sites were established in a star configuration based on a 7.62 m square grid (Figure 1). There were a total of 572 sampling sites in field 1 and 541 sampling sites in field 2 during 1997, but in 1998 there was a total of 571 sampling sites in field 1 and 536 sampling sites in field 2. However, due to mishandling of pots, pigweed seeds were only analyzed at a total of 564 sampling sites in field 1 and 539 sampling sites in field 2 during 1997, and at 560 sampling sites in field 1 and 539 observations in field 2 during 1998. All observations were referenced with an OmniSTAR 7000[1] differential global positioning system.

Weed sampling. Viable pigweed spp. seed was saved from seedbank samples collected in an experiment to study the spatial distributions of weed seedbanks in these fields (Wiles and Westra 1999). At each sampling site, a soil core of 5 cm in diameter by 10 cm deep was extracted immediately after corn planting in 1997 and 1998. Each soil core was subjected to a high-pressure water bath within a elutriator to isolate seeds from soil

particles (Wiles et al. 1996). After elutriation, seeds from each soil core were dried for 24 hours at 25°C, viable pigweed seed was separated and counted then stored in capped glass vials at ambient temperature from 6 to 12 months. Pigweed seedlings or mature plants were counted when corn was at a four-leaf stage, following a postemergence herbicide treatment, at each sampling site with a 1.52 by 0.15 m quadrat in 1997 and 1998.

Triazine-resistance screening. Pigweed seed were allowed to germinate and then were screened for triazine-resistance. Preliminary studies were conducted to determine optimal conditions for seed germination and growth and uniform herbicide coverage in the chamber sprayer. Seeds were treated with a 0.01 M ethanol solution for two hours to initiate germination (Taylorson 1989) and planted at a depth of 1 cm in 16 x 5 x 5 cm potting containers filled with an organic potting mix[2]. Seeds were evenly spaced within each container at a maximum density of 10 seeds per pot to optimize herbicide coverage; soil cores with more than 10 seeds were planted in additional containers. Pots were placed in a growth chamber for approximately three days or until cotyledons emerged and then moved to the greenhouse. The growth chamber supplied continuous light and temperature (25 C) necessary for germinating pigweed seeds. After pigweed cotyledons emerged, pots were moved to the greenhouse. Greenhouse conditions supplied 26/22 C (day/night) temperatures and a sixteen-hour photoperiod. Natural light was supplemented with 150 watt sodium halide lamps. Seedlings were watered as needed. Emerged seedlings were counted and atrazine was applied at the four-leaf stage. Each container was treated with atrazine at 2.0 kg ai ha^{-1} plus crop oil concentrate[3] at 1.0%

(v/v). Atrazine was applied with an overhead track sprayer. The sprayer was equipped with an 8002E flat-fan nozzle and delivered 140 L/ha at 210 kPa. Surviving seedlings were counted 21 DAT and determined to be triazine resistant.

Soil sampling. Soil organic matter, pH, sand, silt, and clay were sampled before crop planting in 1997 (Fleming et al. 1999). A 76.2 m square grid was established within each field then a sampling site was established within each grid cell. At each site, a 5.1 cm diameter by 31 cm deep soil core was taken and analyzed for soil organic matter and texture. Individual sampling sites for weed seedbank and soil attributes did not coincide but sampling sites for weed seedbank and soil attributes did represent the same field area (a 23223 m^2 square area).

Correlation analysis. Inverse distance weighted soil attribute maps were created using ArcView[4] software. In this analysis, twelve nearest neighbors (sampling units) were used to determine each interpolated value with distance power set at two. The power of two is commonly selected to limit the influence of distant sampling units on the interpolated value (Gotway et al. 1996). Then a data set containing interpolated soil attribute values that corresponded to the cumulative triazine resistant pigweed seedbank population between 1997 and 1998 was created. Nonparametric Spearman rank correlation coefficients (r_s) (Rees 1989) were calculated as a measure of correlation between resistant pigweed seedbank populations between years in each field, with the weed seedling population for each year and field, and between resistant pigweed seedbank populations and soil attributes (pH, soil organic matter, clay, silt, and sand content).

RESULTS AND DISCUSSION

Pigweed seedlings resistant to atrazine herbicide were detected. A total of 6811 pigweed seeds in field 1 and 3974 pigweed seeds in field 2 during 1997 were screened for resistance to atrazine. In 1998, a total of 1898 pigweed seeds in field 1 (pigweed seed density in 1998 was 3 times less than pigweed seed density in 1997) and 968 pigweed seeds in field 2 (pigweed seed density in 1998 was four times less than pigweed seed density in 1997) were screened for resistance to atrazine. The median pigweed seedbank density per soil core during 1997 and 1998 in field 1 was 3 pigweed seeds and for field 2 the median pigweed seed density was 3 during 1997 and 2 in 1998 (Table 2). Pigweed germination in field 1 was 71% (1997) and 76% (1998) and germination in field 2 was 69% (1997) and 67 % (1998).

From these populations in field 1, there were 34 uninjured pigweed seedlings found in 27 soil cores (5% of the soil cores) during 1997 and there were 24 uninjured pigweed seedlings in 19 soil cores (3% of the soil cores) for the 1998 sample (Figure 2). For field 2, all of the pigweed seedlings from the 1997 sample treated with atrazine were killed, but 11 pigweed seedlings found in 7 soil cores were unaffected by the herbicide treatment for the 1998 sample (1% of the soil cores) (Figure 3). After frequent use of triazine herbicides in field 1 (Rothe 1998), triazine resistant pigweed populations may have developed (Eberlein et al. 1992).

Results of Spearman rank correlation analysis shows the density of resistant pigweed in field 1 was significantly correlated between years with a low correlation coefficient of 0.09 at $P \leq 0.05$. From these results it is suggested the detected resistant pigweed density was only moderately consistent between years (Figure 2). Suspected

resistant pigweed populations were more often detected within the south half than the north half of field 1 during 1997 (within 23 soil cores in the south half verses four soil cores in the north half) and 1998 (within 14 soil cores in the south half verses five soil cores in the north half) (Figure 1) which may indicate differences in atrazine distribution and persistence in this field. In addition, the density of resistant pigweed in field 1 during 1997 was moderately correlated (Figure 4) with the density of pigweed seedlings, after the postemergence herbicide treatment was applied in 1997 (correlation coefficient of 0.12 at $P \leq 0.05$) and 1998 (correlation coefficient of 0.14 at $P \leq 0.05$). Spearman rank correlation coefficient values close to zero for field 1 in 1997 and 1998 may be due to too few soil cores that contained a resistant pigweed. Atrazine was applied postemergence in each field in 1997 and 1998 (Table 1). These results suggest the seedling population that remained after a postemergence application of atrazine may have been resistant to atrazine. Spearman rank analysis was not conducted for resistant populations between years for field 2 because there was no resistant pigweed population detected in 1997. Also, there was no significant Spearman rank relationship between the resistant pigweed density and the weed seedling density after a postemergence herbicide was applied in field 2 for both years.

Spearman rank analysis was conducted to investigate the possible relationship of the suspected resistant pigweed population with soil attributes (Figure 5). Significant correlation coefficient values ranged from –0.16 to 0.20 when soil attributes and resistant pigweed densities in 1997 and 1998 for field 1 were evaluated (Table 3). There was no significant correlation between soil attributes and resistant weed populations in field 2 for both years. However, in field 1 during 1997, triazine resistant pigweed seedbank

population was positively correlated with organic matter and clay and negatively correlated with sand (Figure 5 and Table 3). These results indicate that as soil organic matter and clay content increased, so did the resistant pigweed density, but as sand content increased the resistant pigweed density decreased. For the 1998 sample for field 1, the suspected triazine resistant pigweed seedbank population was again correlated with clay but not with the other soil attributes (Table 3). Soil pH was not significantly correlated with the triazine resistant pigweed seedbank density in either field (Table 3). In this study soil pH ranged from 7.0 to 8.0 in these two fields and none of the suspected triazine resistant pigweed populations were correlated with pH. Atrazine applied to soils with a pH of 7 or greater will be less sorbed to soil surfaces and likely transported with water from the point of application (Clay and Koskinen 1990; Koskinen and Clay 1997). In particular, clay may indirectly relate to atrazine resistant pigweed populations in this field because clay was positively correlated with the suspected triazine resistant pigweed seedbank population in 1997 and 1998. However, additional fields should be evaluated to verify if clay content would be a consistent indicator of pigweed seedbank triazine resistance.

There was little variability in the soil attributes that were evaluated in these two fields. Soil texture for both fields was classified as either sand or loamy-sand. In particular, sand content ranged from 71.5 to 92.0%, silt ranged from 0.93 to 16.6%, and clay ranged from 4.1 to 15.6% within both fields (Table 4). Organic matter was also low, ranging from less than 1 to 2% (Table 4). The low detection of resistant pigweed seedlings in either field may be due to the low persistence of atrazine in sand and sandy-loam soils within these fields. Studies that investigated atrazine leaching through soil

columns indicated that atrazine initially remains at the soil surface as a result of sorption processes (Koskinen and Clay 1997). However, columns packed with sand indicated that 9% of the atrazine applied moved to a depth of 40 to 80 cm in 22 weeks (Wietersen et al. 1993). This rapid movement of atrazine away from the zone of application is due to the high pore space and lower water holding capacity of sand particles (Koskinen and Clay 1997). For sandy loam soils atrazine movement away from the site of application was less than in sandy soils. In a study by Sorenson et al. (1993), only 0.3% of the atrazine applied to a 120 cm soil column filled with sandy loam, moved to 80 cm within 78 weeks.

Weed and crop management could be more efficient if the producer had more accurate, field specific information about the spatial variability of soil and landscape attributes that promote herbicide resistant weed populations. Future studies are needed to determine if resistant weed populations also correlate with soil and landscape attributes that sustain herbicide persistence. If so, then these indicators could be used to predict areas that promote resistant weed populations in other fields. Identifying field areas that promote resistance to herbicides, would allow a producer to selectively manage field areas differently to minimize selection pressure.

Managing the variability of weed populations in a field with appropriate treatments requires sufficiently accurate information of the population distribution and density. Field maps that show areas that promote a herbicide resistant weed population could be used to enhance weed management decisions and apply appropriate treatments to selected field areas. There is a need to evaluate the spatial distribution of herbicide resistant weed populations and herbicide persistence within a field to enhance weed

management. Currently there has only been one paper that has addressed the spatial variability of a herbicide, atrazine, and its distribution at the field scale. Novak et al. (1997) determined that less atrazine was adsorbed by soils from upland shoulder slopes than by soil in level and depression areas (potholes). To reduce selection pressure and the development of weed resistance to herbicides, a better understanding of herbicide persistence across field landscapes is needed.

SOURCES OF MATERIAL

[1]OmniSTAR, INC, 8200 West glen, Houston, TX 77063, USA.

[2] Metro-Mix 350 Scotts-Sierra Horticultural Products Co., Marysville, OH
Grace-Sierra 1000, Milpitas, CA

[3] Crop oil concentrate (8 % paraffin base petroleum oil and 17 % emulsifier) was Prime Oil, Riverside/Terra Corp., Terra Centre, 600 Fourth Street, Sioux City, IA 51101.

[4]ArcView GIS. 1996. Environmental Systems Research Institute Inc., Redlands, CA

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Table 1. Herbicides applied to fields 1 and 2 during 1997 and 1998.

Field	Year	Application Time	Herbicide treatment	Rate
				Kg ai ha^{-1}
1	1997	PRE[a]	Glyphosate + Atrazine	1.12 + 2.02
		POST	(Nicosulfuron + Rimsulfuron + Atrazine)	(0.84)[b]
1	1998	PRE	Metolachlor + Cyanazine	2.18 + 2.24
		POST	(Nicosulfuron + Rimsulfuron + Atrazine) + diglycolamine	(0.84) + 0.14
2	1997	PRE	Glyphosate + Metolachlor	1.12 + 1.94
		POST	Pyridate + Atrazine	0.91 + 2.02
2	1998	POST	(Nicosulfuron + Rimsulfuron + Atrazine) + Pyridate	(0.84) + 0.49

[a] Abbreviations: PRE, preemergence; POST, postemergence.

[b] Items in parentheses ( ) indicate a premix.

Table 2. Pigweed seedbank infestation for fields 1 and 2 in 1997 and 1998.

Field	Species	Mean (Standard deviation)		Median		Maximum	
		1997	1998	1997	1998	1997	1998
		Number of pigweed seeds per soil core					
1		12.1 (62.7)	3.9 (4.3)	3	3	1380	38
2		7.4 (20.1)	2.6 (2.9)	3	2	308	45

Table 3. Spearman rank correlations between the resistant pigweed seedbank populations in 1997 and 1998 with soil attributes for field 1.

Year	OM	pH	Sand	Silt	Clay
			r_s[a]		
1997	0.12*	-0.06	-0.16*	0.07	0.20*
1998	0.03	-0.04	-0.06	0.04	0.09*

[a](*) Indicate correlation coefficient was significant at $P \leq 0.05$.

Table 4. Soil attributes in fields 1 and 2.

Field	Soil attribute	Mean (Standard deviation)	Minimum	Maximum
		%		
1	Organic matter	1.0 (0.2)	0.7	2.0
	pH	7.6 (0.1)	7.1	8.0
	Sand	85.4 (3.5)	76.1	92.0
	Silt	5.6 (1.7)	0.9	10.3
	Clay	9.0 (2.4)	4.1	15.6
2	Organic matter	1.1 (0.1)	0.5	1.5
	pH	7.6 (0.1)	7.1	8.0
	Sand	79.9 (4.1)	71.5	92.0
	Silt	10.4 (2.6)	4.3	16.6
	Clay	9.6 (2.1)	5.6	14.6

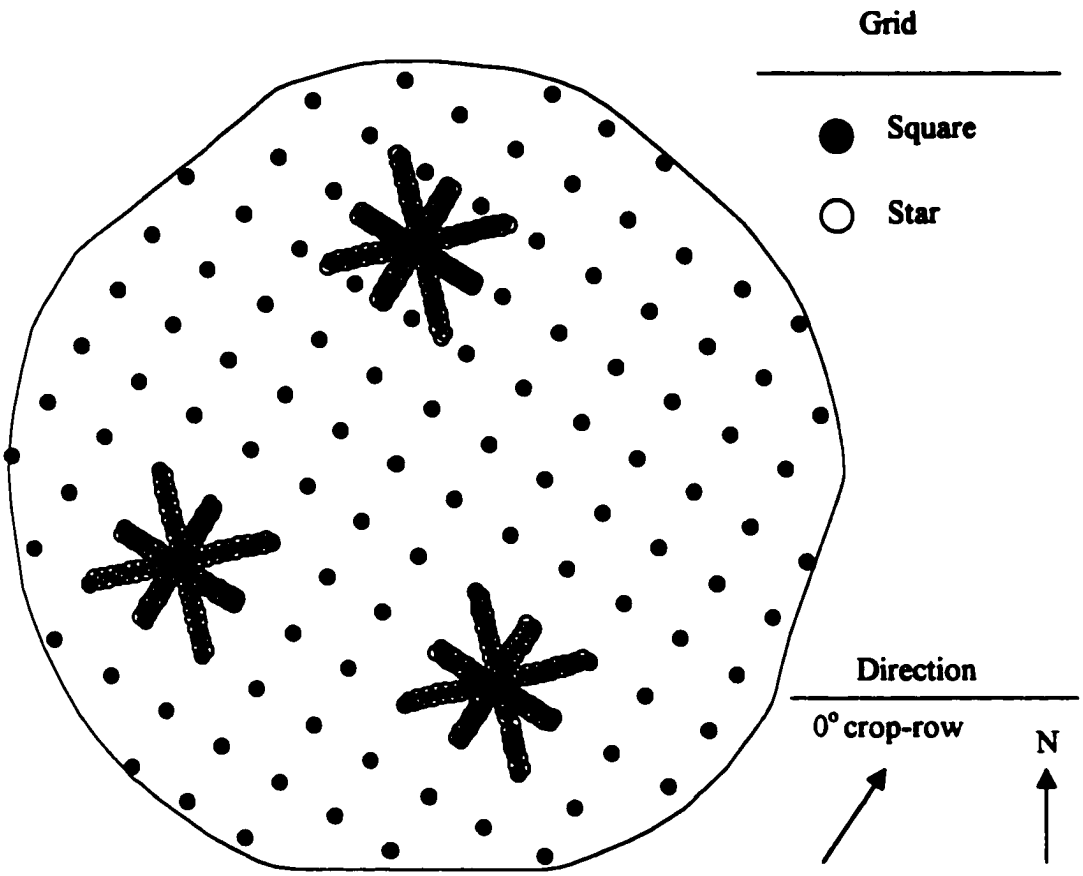

Figure 1. Placement of sampling units in field 1. Sampling unit placement was similar in field 2.

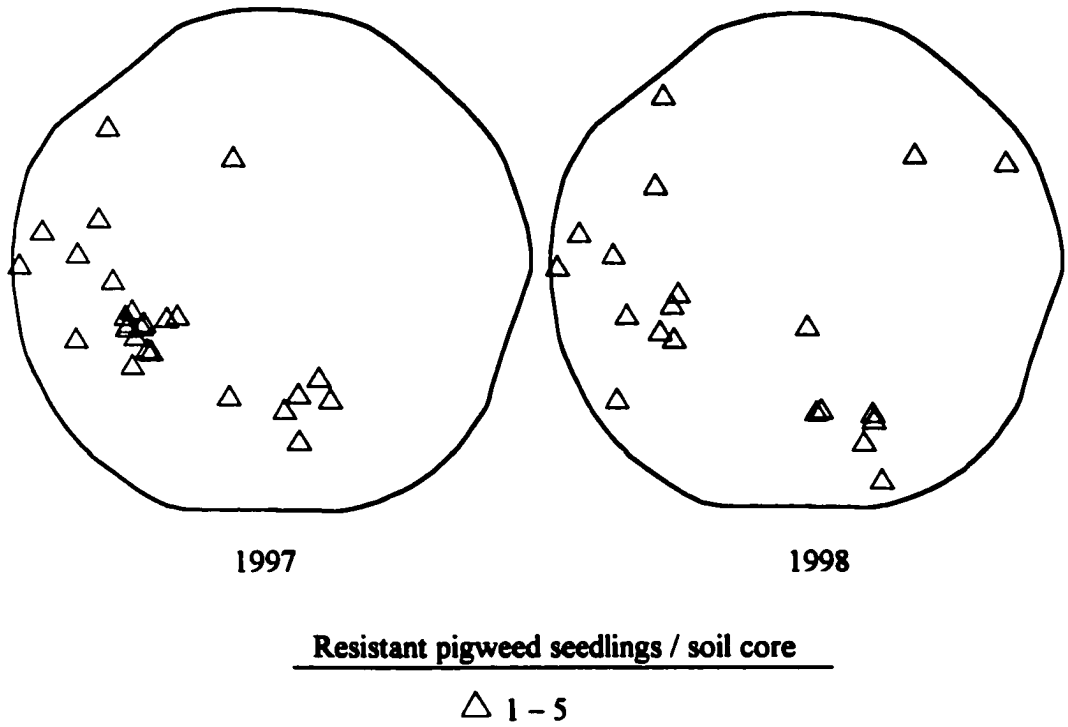

Figure 2. The presence of triazine resistant pigweed spp. during 1997 and 1998 for field 1.

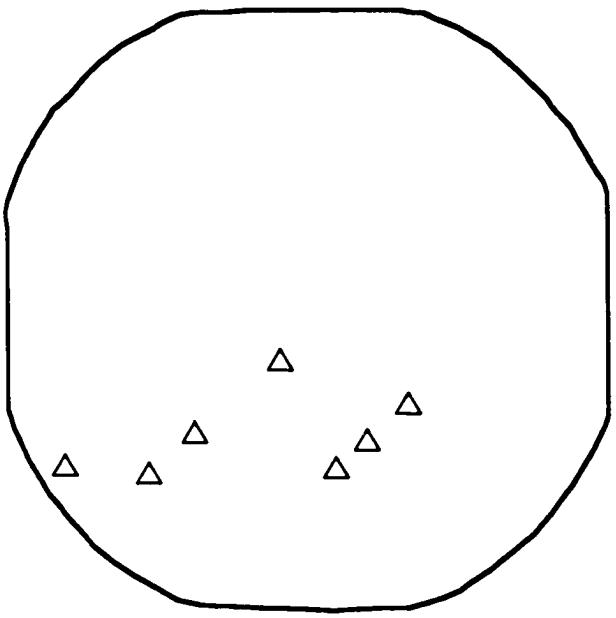

Figure 3. The presence of triazine resistant pigweed spp. during 1998 for field 2.

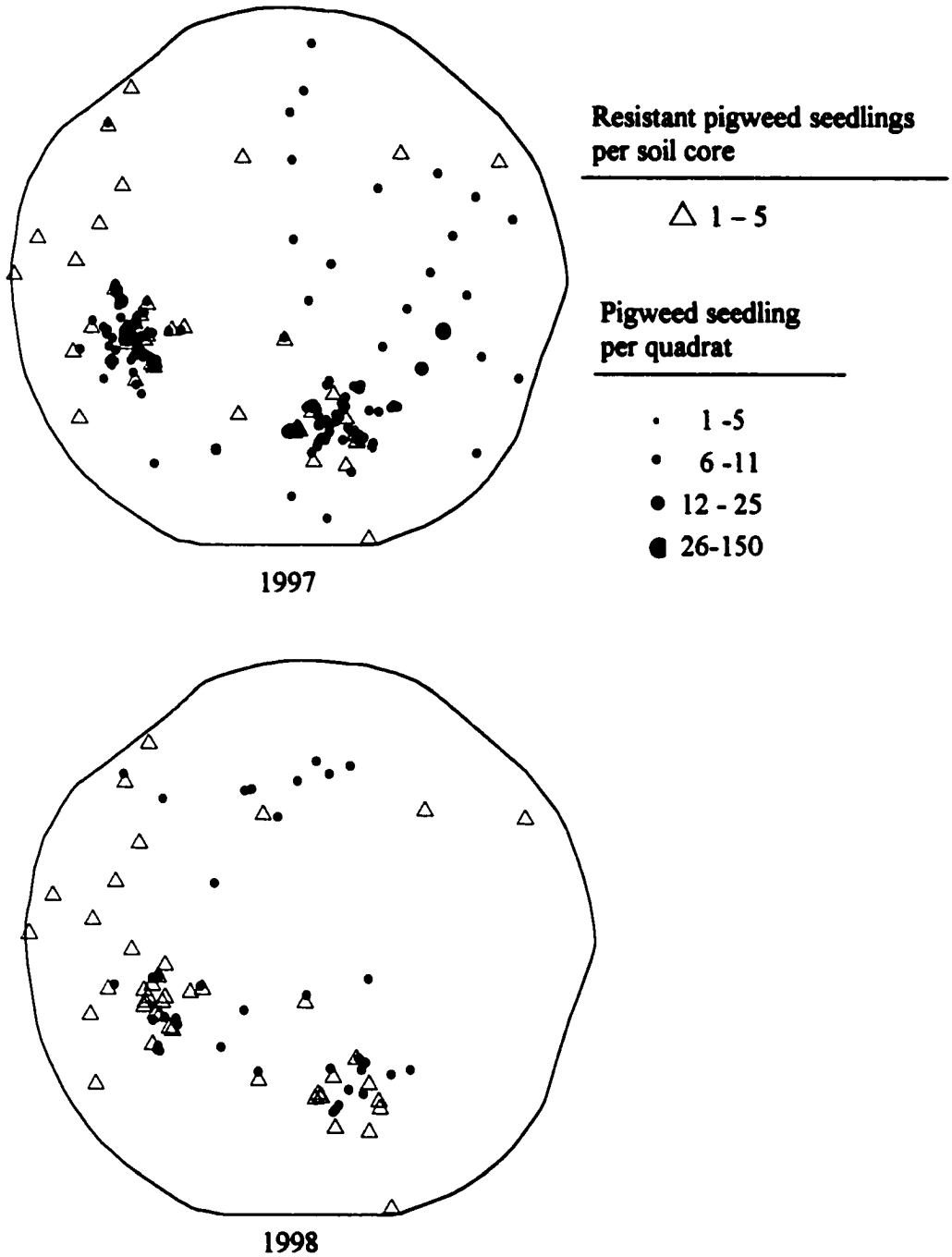

Figure 4. Sites where pigweed seedling and triazine resistant pigweed seedbank populations were detected during 1997 and 1998 for field 1.

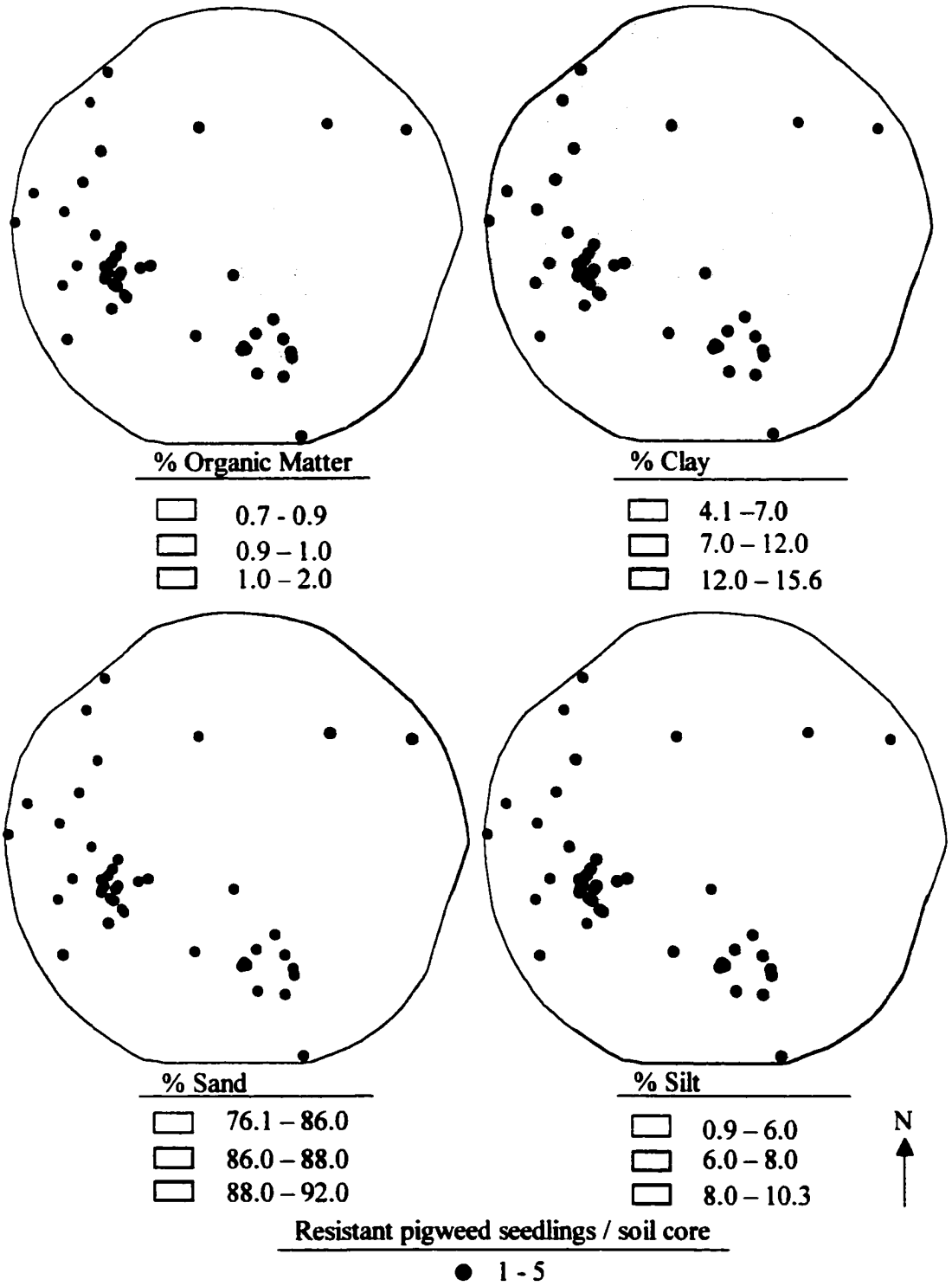

Figure 5. Triazine resistant pigweed seedbank population during 1997 and 1998 with organic matter, clay, sand, and silt for field 1.

Conclusions for Each Chapter

Conclusions for Each Chapter

Chapter 1

1. The lack of detectable spatial dependence for 86 of 93 samples with the employed sampling method suggests weed seedling densities in eastern Colorado irrigated corn fields are not correlated at separation distances at or greater than 7.62 m and interpolated maps based on grid sampling at these scales should not be used because knowing a weed density at one field location would not provide any information about the weed density at an unsampled location with the employed sampling method.

2. Field sandbur densities were correlated at greater distances in the direction of the crop row than the other examined directions. Future sampling plans, if and when sampling at the scale of spatial dependence is possible, to create a reliable interpolated distribution map of weed densities in eastern Colorado irrigated corn fields, should include observations at shorter separation distances for directions from the crop row than down the crop row.

3. In one field, spatial correlation of common lambsquarters densities was only detected in the field area where sugar beet was previously planted. Future sampling plans, if and when sampling at the scale of spatial dependence is possible, to create a reliable interpolated distribution map of weed densities in eastern Colorado irrigated corn fields, should include observations at shorter separation distances when a field has been previously planted to certain crops.

4. Future sampling methods to evaluate spatial dependence of weed seedlings in eastern Colorado corn fields should include observing seedling densities at separation distances less than 7.62 throughout the entire field in multiple directions.

5. For now, grid sampling may be too labor intensive and expensive to adequately map the total weed infestations in eastern Colorado irrigated corn fields. It has been determined that the average cost of counting and identifying weed seedlings is 0.08 dollars per quadrat (Wiles and Schweizer 1999). Based on this cost estimate, it would cost 128 dollars to count and identify weeds in a 53 ha field on a 18 m square (smallest detected range of spatial dependence among the species) grid.

Chapter 2.

1. Results from this study suggest that spiral and stunt nematode densities may correlate with field attributes of sand, silt, clay, and organic matter, but additional research is needed before these attributes are used to determine nematode densities for creating reliable nematode density maps.

2. The lack of detectable spatial dependence for 9 of the 12 samples with the employed sampling method suggests nematode densities in eastern Colorado corn fields are not correlated at separation distances at or greater than 76.2 m and interpolated maps based on grid sampling at these scales should not be used because knowing a nematode density at one field location would not provide any information about the nematode density at an unsampled location.

3. For now, sampling spiral and lesion nematodes for map generation would be very costly. For example, it may cost 1,000 dollars to count and identify plant-parasitic nematodes in a 53 ha field using a 76.2 m square grid.

4. Future sampling plans to evaluate spatial dependence of plant-parasitic nematode infestations in eastern Colorado corn fields should include observing nematode densities at separation distances less than 76.2 m and possibly during active corn growth.

Chapter 3

1. The lack of significant correlations between rootworm egg densities and organic matter, sand, silt, and clay content suggests that these soil properties would be poor indicators of rootworm egg densities in eastern Colorado corn fields.

2. The lack of detectable spatial dependence for 3 of the 4 samples with the employed sampling method suggests rootworm egg densities in eastern Colorado corn fields are not correlated at separation distances at or greater than 76.2 m and interpolated maps based on grid sampling at these scales should not be used because knowing a rootworm egg density at one field location would not provide any information about the rootworm egg density at an unsampled location.

3. Future sampling plans to evaluate the spatial dependence of rootworm egg infestations in eastern Colorado corn fields should include observing rootworm egg densities at separation distances less than 76.2 m.

Chapter 4

1. Atrazine resistant pigweed seedbank populations were detected in these two fields and possibly could be detected in other fields with the employed sampling plan.

2. Soil clay content may be an indicator of atrazine resistant pigweed populations in eastern Colorado corn fields because clay content was positively correlated with resistant pigweed seedbank populations in both years of the study.