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The Potential for Mapping Nematode Distributions for Site-specific Management[1]

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Abstract: The success of site-specific nematode management depends on a grower or advisor being able to afford to make a map of an infestation that is accurate enough for management decisions. The spatial dependence of nematode infestations and correlation of soil attributes with nematode density were assessed to investigate the scale of sampling required to obtain correlated observations of density and the use of soils data to reduce the cost of sampling. Nematodes and soil were sampled on a 76.2 × 76.2-m grid in two irrigated corn (*Zea mays*) fields for 2 years. Nematodes of each of three species were found in 36% to 77% of the cores from a field. Spatial dependence was detected for 10 of 16 distributions, and 22% to 67% of the variation in density within a field could be attributed to spatial correlation. Density was correlated to distances of 115 to 649 m in the directions of 0, 45, 90, and 135° from the crop row, and distances varied with direction. Correlations between nematode density and soil attributes were inconsistent between species and fields. These results indicate a potential for mapping nematode infestations for site-specific management, but provide no evidence for reducing the cost of sampling by substituting soils data for nematode counts when making a map.

Key words: anisotropy, correlation, geostatistics, map, nematode, organic matter, sampling, site-specific management, soil texture, spatial dependence, spatial distribution.

Plant-parasitic nematodes that inhabit agricultural fields feed on roots and can decrease yields (Todd and Oakley, 1996). When infestations are large, producers are often advised to treat infested fields with a nematicide, grow a resistant crop variety, or rotate to a less susceptible crop or variety (Akhtar, 1997). To minimize management costs and reduce the use of nematicides, growers are often interested in identifying and treating only the nematode-infested areas in a field (Evans et al., 1999). Precision farming technology makes this possible.

The success of site-specific nematode management depends on an affordable map of the nematode distribution within a field as the basis for making management decisions. The cost of sampling and making the map must be less than the cost reduction of site-specific management. Given the expense of counting and identifying nematodes, methods to minimize the number of observations required to make a map are needed, sampling must be as efficient as possible, and the most appropriate method of interpolation for making the map must be used.

The cost of sampling may be reduced if nematode density is consistently correlated with a field characteristic that is less expensive to sample. In that case, observations of the characteristic may be substituted for the more expensive observations of nematode density or a map of the correlated characteristic may be used to target nematode sampling to where there is the most uncertainty about the management decision (Dieleman and Mortensen, 1999; Heisel et al., 1999). Field characteristics that have a 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).

The optimal sampling plan for a spatially varying attribute depends on the spatial dependence of the distribution (Flatman et al., 1988; Gotway et al., 1996; Oliver et al., 1997). When a distribution has spatial dependence, the value at one location and the values at other locations are correlated as a function of distance and direction (Rossi et al., 1992; Weisz et al., 1995). When the spatial dependence is known, the value at an unsampled location can be predicted from values at sampled locations and the relative positions of the samples. The cost of sampling soil characteristics is reduced and the quality of the information obtained is improved by selecting the sampling grids, number of observations, use of composite samples, and interpolation based on the spatial dependence of soil characteristics (Burrough, 1991).

Spatial dependence can be described using geostatistical analysis (Rossi et al., 1992). Geostatistics can be used to quantify the average distance of spatial correlation by direction, and the variability of observations that are separated by very short distances. Geostatistical analyses have been used to describe spatial dependence of plant-parasitic nematode densities within fields (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). When spatial dependence was detected in those studies, nematode density was correlated over a wide range of distances—from less than 1 m to 160 m.

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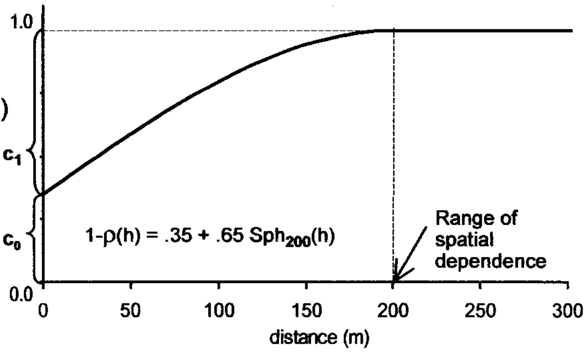

Fig. 1. Example of a spherical correlogram model in variogram form.

The purpose of this work was to investigate the spatial dependence of nematode densities and correlations between nematode density and soil organic matter and texture within fields at a scale appropriate for using precision farming technology to assess, map, and manage variability. These data should facilitate the assessment of the feasibility of site-specific nematode management and the design of cost-effective sampling programs for mapping distributions.

Materials and Methods

Field sites: Nematode infestations were sampled in 1997 and 1998 in two center-pivot irrigated corn fields (71 and 53 ha) in Morgan County, Colorado. Soils in both pivots included 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). No nematicide was applied in either year, and both fields were well irrigated.

Sampling: Nematode and soil sampling was done as part of an experiment to identify factors that affect the variability of yield within fields (Heermann et al., 1999). Each field was divided into a square grid with 76.2 m between samples for nematodes, soil, weeds, insects, plant population, and other factors affecting yield at the same scale throughout the entire field. Sample locations were referenced with an OmniSTAR 7000 (OmniSTAR, Houston, TX) differential global positioning system.

Soil cores for nematode counts were collected at the center of each square grid cell less than 1 week after corn harvest and before fall tillage. In 1997, field 1 was sampled on October 27 and field 2 on October 6. In 1998, field 1 was sampled on November 9 and field 2 on November 17. The number of cores collected was 122 (field 1) and 91 (field 2) in 1997, and 121 (field 1) and 86 (field 2) in 1998. Cores (5-cm-diam. × 10-cm-deep) were collected in the corn row next to a corn plant, and a 100-g sub-sample was analyzed for nematode identification and enumeration by the Kansas State University Plant Nematology Laboratory. Nematodes were extracted from soil using methodology based on Jenkins (1964).

Samples for the soil analyses were collected at a randomly selected location within each square grid cell before crop planting in 1997 (Fleming et al., 1999). At each site, a 5.1-cm-diam. × 31-cm-deep soil core was collected and analyzed for soil organic matter and texture. The average distance between cores collected for nematode and soil sampling within a square grid cell was 25 m and was as small as 2 m and as large as 55 m.

Geostatistical analysis: The spatial distribution of each plant-parasitic nematode species was quantified by describing the spatial dependence of each sample with correlograms. A sample is defined as all observations for a combination of a field, year, and a species or the total infestation in a field. A correlogram is a plot of correlation coefficients for observations separated by a specific distance (h) in a particular direction:

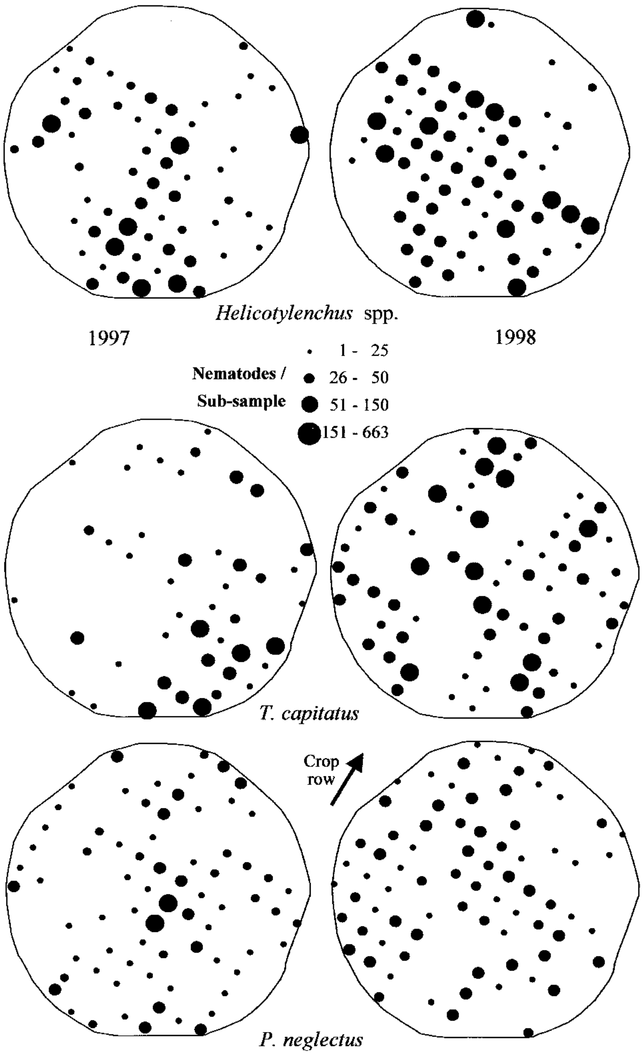

Fig. 2. Sample data from 1997 and 1998 for *Helicotylenchus* spp., *Tylenchorhynchus capitatus,* and *Pratylenchus neglectus* collected on a square grid with 76.2 m between observations in field 1.

TABLE 1. Summary statistics for nematode infestations in 1997 and 1998 in two irrigated corn fields.[a]

		Mean (standard deviation)		Median		Maximum		Sub-samples with nematodes (%)	
Field	Species	1997	1998	1997	1998	1997	1998	1997	1998
1	*Helicotylenchus* ssp.	35.5 (85.6)	47.3 (65.4)	4.5	21.5	638	309	50	55
	Tylenchorhynchus capitatus	26.2 (82.3)	53.3 (7.47)	0.0	19.0	663	383	36	58
	Pratylenchus neglectus	20.2 (30.6)	28.3 (32.0)	10.0	20.0	164	148	59	63
	Total	81.9 (136.7)	128.8 (122.0)	42.5	103.5	897	497	83	97
2	*Helicotylenchus* spp.	86.2 (106.8)	110.5 (139.0)	32.0	53.0	420	731	70	77
	Tylenchorhynchus capitatus	56.6 (120.5)	136.4 (207.2)	20.0	71.0	951	1,543	56	70
	Pratylenchus neglectus	21.5 (39.5)	21.0 (29.5)	10.0	10.5	264	119	56	50
	Total	164.2 (177.8)	267.9 (262.5)	98.0	222.5	961	1,727	93	97

[a] Values expressed as number of nematodes per 100 g soil sub-sample.

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

where N(*h*) is the number of pairs of points separated by *h*, a separation vector; v_i is the observation at location *i;* and v_j is the observation at location *j* that is separated from location *i* by the vector *h* (Isaaks and Srivastava, 1989). The values of $m_{(-h)}$ and $\sigma_{(-h)}$ are the mean and standard deviation of the observations whose locations are −h away from some other observation, and m_{+h} and $\sigma_{(+h)}$ are the mean and standard deviation of the observations whose locations are +h away from some other observation.

Both sample and theoretical correlograms were calculated using SAGE95 (Isaaks & Co., San Mateo, CA). This program expresses correlograms in variogram form (one minus each correlogram value) for interpretation of parameters and graphs. Sample correlograms were calculated for the directions of 0, 45, 90, and 135° from the crop row with a lag distance of 76 m for 0 and 90° and 107 m for 45 and 135° for both the sample and

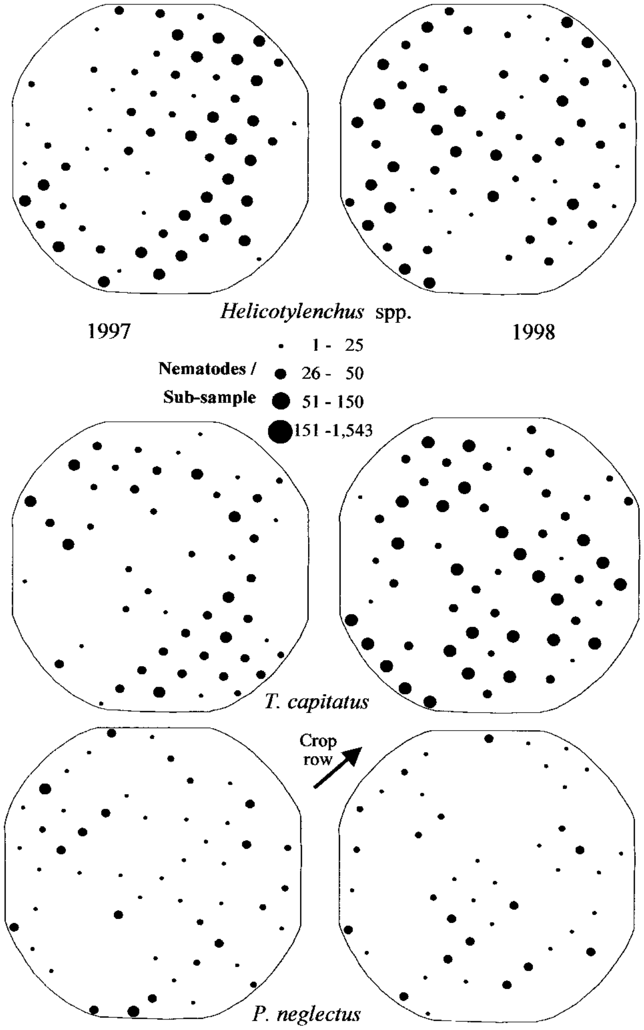

FIG. 3. Sample data from 1997 and 1998 for *Helicotylenchus* spp., *Tylenchorhynchus capitatus,* and *Pratylenchus neglectus* collected on a square grid with 76.2 m between observations in field 2.

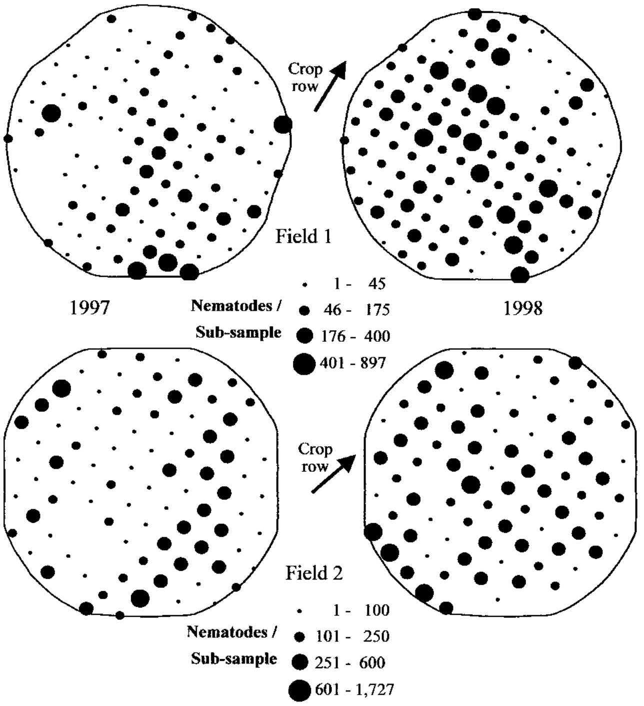

FIG. 4. Sample data collected on a square grid with 76.2 m between observations for the total nematode infestations in two irrigated corn fields in 1997 and 1998.

TABLE 2. Parameters of directional correlograms in variogram form describing the spatial dependence of distributions of nematodes in two irrigated corn fields.

					Range of spatial dependence[a,b]			
					Direction from the crop row[c]			
Field	Year	Species	c_0	c_1	0°	45°	90°	135°
1	1997	*Helicotylenchus* spp.	0.43	0.57	257	217	282	390
		Pratylenchus neglectus	0.65	0.35	325	208	126	143
		Tylenchorhynchus capitatus	0.62	0.38	159	373	393	161
		Total	0.54	0.46	279	292	273	262
	1998	*Helicotylenchus* spp.	0.53	0.47	270	272	649	630
		Pratylenchus neglectus	0.78	0.22	233	221	422	529
		Tylenchorhynchus capitatus			152–228[d]	—	—	—
		Total	0.66	0.33	269	195	202	289
2	1997	*Helicotylenchus* spp.	0.33	0.67	194	115	123	245
		Pratylenchus neglectus			—	—	—	—
		Tylenchorhynchus capitatus	0.73	0.27	340	288	249	280
		Total	0.60	0.40	291	122	123	299
	1998	*Helicotylenchus* spp.			—	—	—	—
		Pratylenchus neglectus			76–152[d]	—	—	—
		Tylenchorhynchus capitatus			—	—	152–228[d]	—
		Total			—	—	—	—

[a] Values expressed as meters.

[b] A dash (—) indicates no spatial dependence was apparent in the directional sample correlogram.

[c] Direction clockwise from the crop row. 0° is the direction of the crop row.

[d] Value of the range estimated from the directional sample correlogram.

modeled correlograms. SAGE95 software uses regression to fit correlogram models and simultaneously fits models to all directional sample correlograms of a distribution, and the variation in spatial dependence with direction (anisotropy) is modeled with an ellipse (Isaaks and Srivastava, 1989). Correlogram values were weighted by the number of pairs per lag, and a spherical model was fit to the correlogram in variogram form:

$$1 - \rho(h) = c_0 + c_1 \cdot \mathrm{Sph}_a(h) \qquad [2]$$

where

$$\mathrm{Sph}_a(h) = \left\{ \begin{array}{ll} 1.5\dfrac{h}{a} - 0.5\left(\dfrac{h}{a}\right)^3 & h \leq a \\ 1 & \text{otherwise} \end{array} \right\} \qquad [3]$$

Spherical models are linear at small lag distances but then flatten out and eventually plateau at the sill (Isaaks and Srivastava, 1989) (Fig. 1). The sill is one for a correlogram. The nugget of a correlogram (c_0) is the discontinuity at 0 m and represents the proportion of the variability in density that may be due to spatial structure below the scale of sampling and experimental or measurement error (Rossi et al., 1992). The value of c_1 is the proportion of the variation in density that can be explained by spatial structure. The distance at which the correlogram reaches an asymptote of one is the range of spatial dependence (a) and is the average distance within which observations remain correlated spatially (Rossi et al., 1992).

Correlation analysis: Maps of soil attributes were created from the sample data with inverse distance weighting using ArcView software (ESRI, Redlands, CA) to estimate soil attributes at each location where nematodes were sampled. Twelve nearest neighbors (cores) were used to determine each interpolated value with distance power set at two to limit the influence of distant observations on the interpolated value (Gotway et al., 1996). Nonparametric Spearman rank correlation coefficients (r_s) (Rees, 1989) were calculated as a measure of the correlation between nematode densities and soil attributes.

RESULTS

Nematode infestation: Nematodes of *Helicotylenchus* spp., *Tylenchorhynchus capitatus* (Allan, 1995), and *Pratylenchus neglectus* (Rensch, 1994) were observed in both fields in both years, but were more abundant in field 2 than field 1 (Table 1; Figs. 2–4). Mean total nematode density for a field ranged from 81.9 to 267.9 nematodes per sub-sample with nematodes found in 83% to 97% of the cores (Table 1; Fig. 4). For individual species, nematodes were found in 36% to 77% of the cores collected in a field and mean densities ranged from 35.5 to 110.5 nematodes per sub-sample for *Helicotylenchus* spp., 26.2 to 136.4 for *T. capitatus,* and 20.2 to 28.3 for *P. neglectus* (Table 1). *Pratylenchus neglectus* was the least abundant species but infested as large an area (as many cores) as the other species (Table 1; Figs. 2,3). There was large variation in density of each species within a field. The standard deviation was greater than the mean for all but three samples, and many sub-samples from a distribution had few or no nematodes and a few cores had very high counts (Table 1). Median counts ranged from 0 to 71 nematodes per sub- sample, but the maximum number of nematodes in a sub-sample ranged from 119 to 1,543.

Spatial dependence: No spatial dependence was detected for three samples from field 2. These were *P. neglectus* in 1997, and total nematodes and *Helicotylenchus* spp. in 1998 (Table 2). Spatial dependence was detected in just one of four directions for *T. capitatus* in field 1 in 1998 and *P. neglectus* and *T. capitatus* in field 2 in 1998. That direction was either parallel or perpendicular to the crop row, and the range of spatial dependence was between 76 and 228 m (Table 2).

For the remaining 10 samples, the variation in nematode density within a field that could be attributed to spatial correlation (c_1) ranged from 22% to 67% for individual species and 33% to 46% for total infestations (Table 2). Density was correlated over distances of 115 to 649 m in the four directions for individual species or 122 to 299 m for total infestations (Table 2; Figs. 5,6). The range of spatial dependence varied with direction for all samples except the total infestation in field 1 in 1997 (Fig. 5A). In that case, the maximum range of spatial dependence for the four directions (292 m for 45°) was just 1.1 times larger than the smallest range (262 m for 135°). The maximum range of the four directions was more than two times larger than the smallest range for 6 of the 10 spatially correlated samples including all species in field 1 except *Helicotylenchus* spp. in 1997 (Table 2; Fig. 5B,C; Fig. 6B). The direction of the maximum range was more often 135° from the crop than any other direction (Table 2). Density was correlated for the longest distance in the direction of 135° from the crop row for five samples, 0° for two samples, 45° for one sample, and 90° for two samples.

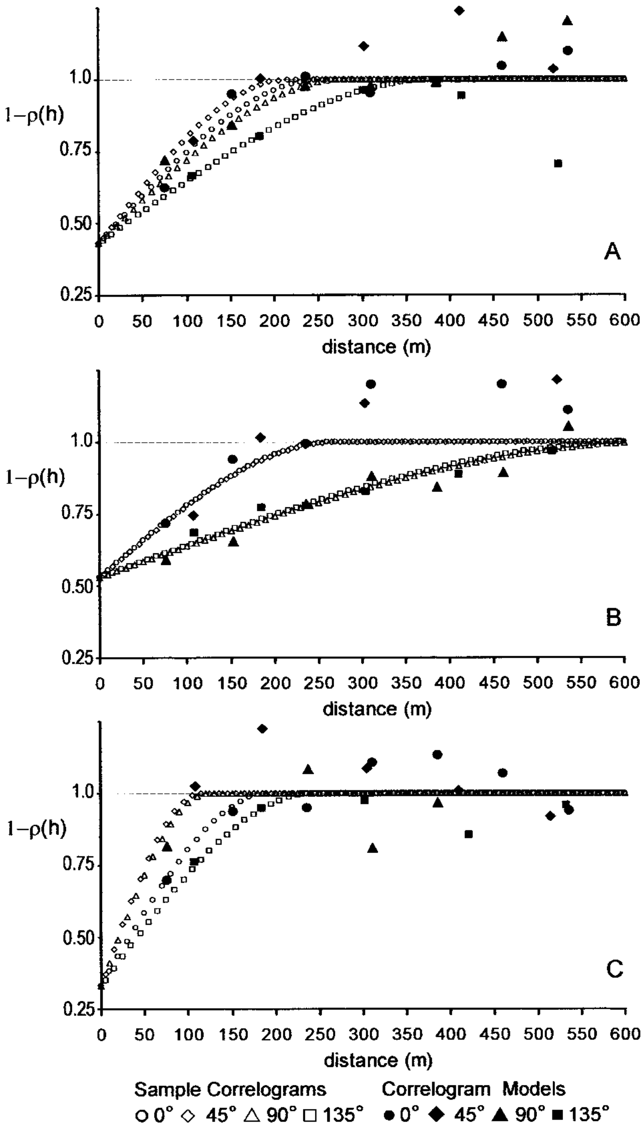

FIG. 5. Directional correlograms in variogram form describing the spatial dependence of the distributions of *Helicotylenchus* spp. in field 1 in (A) 1997, (B) 1998, and (C) in field 2 in 1997.

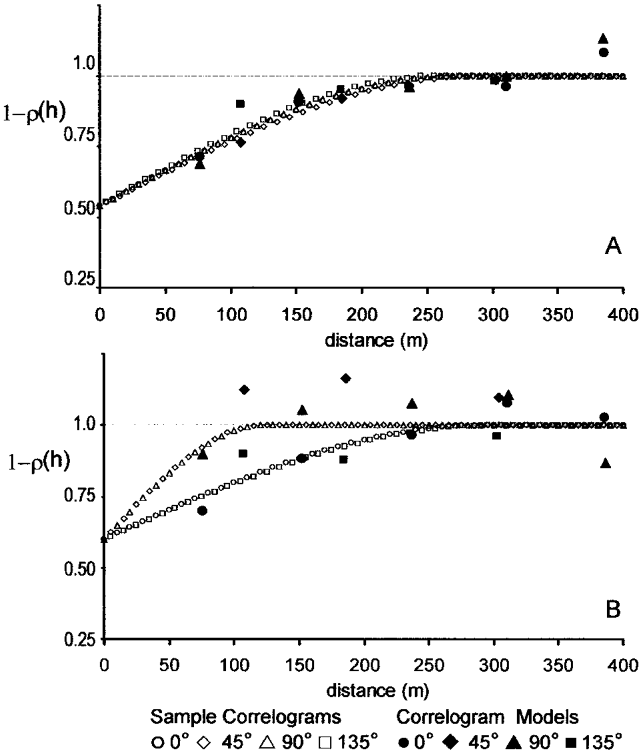

FIG. 6. Directional correlograms in variogram form describing the spatial dependence of the distributions of the total nematode infestation in 1997 in (A) field 1 and (B) field 2.

Correlation between nematode density and soil attributes: Twenty of the correlations between nematode density and soil attributes were significant ($P \leq 0.05$), with density correlated with each attribute in at least one case (Table 3). The magnitude and signs of the correlations were similar for *Helicotylenchus* spp. in field 1 for both years, and the strongest correlations were with sand and organic matter (Table 3; Fig. 7). Density was negatively correlated with sand (r_s = −.39 in both 1997 and 1998) but was positively correlated with organic matter (r_s = .44 and .49) as well as silt (r_s = .23 and .28) and clay (r_s = .36 and .31). Total infestation and density of *T. capitatus* were significantly correlated with all soil attributes in field 2 in 1998, but the correlations were opposite in

TABLE 3. Correlation between soil attributes and nematode density within two irrigated corn fields.

		Species[a,b]							
		Helicotylenchus spp.		*Tylenchorhynchus capitatus*		*Pratylenchus neglectus*		Total	
Field	Soil attribute	1997	1998	1997	1998	1997	1998	1997	1998
1	Organic matter	0.44**	0.49**	0.03	−0.07	0.01	0.00	0.22*	0.22*
	Sand	−0.39**	−0.39**	0.02	0.14	0.09	0.00	−0.13	−0.14
	Silt	0.23**	0.28**	0.14	−0.08	−0.09	−0.12	0.11	0.09
	Clay	0.36**	0.31**	−0.09	−0.14	−0.06	0.06	0.10	0.09
2	Organic matter	−0.10	0.09	−0.47**	−0.21	−0.02	0.08	−0.22*	−0.06
	Sand	0.21	−0.16	0.46**	0.21	0.13	−0.12	0.28**	0.00
	Silt	−0.11	0.23*	−0.54**	−0.26*	−0.08	−0.27	−0.26*	−0.03
	Clay	−0.29**	0.05	−0.21	−0.07	−0.09	0.22	−0.23*	0.05

[a] Spearman rank correlation coefficients (r_s).

[b] * $P \leq 0.10$, ** $P \leq 0.05$.

sign of those of *Helicotylenchus* spp. in field 1. Density of *T. capitatus* was positively correlated with sand ($r_s = .46$) and negatively correlated with organic matter ($r_s = -.47$), silt ($r_s = -.54$), and clay ($r_s = -.21$) (Table 3; Fig. 8). The other significant correlations were for a single attribute for a sample in 1 year, except total density in field 1 was positively correlated with organic matter in both years ($r_s = .22$) (Table 3).

DISCUSSION

This study indicates a potential for mapping distributions of nematodes for site-specific management. It provides no evidence for reducing the cost of sampling for mapping distributions by substituting soil data for nematode counts or using maps of soil attributes to target nematode sampling to where there is the most uncertainty about the management decision. Observations must be correlated to make a map (Flatman et al., 1988). Spatial dependence was detected for 10 of 16 samples. For the six samples without spatial dependence, density may have been spatially correlated—but only for distances less than the minimum spacing of

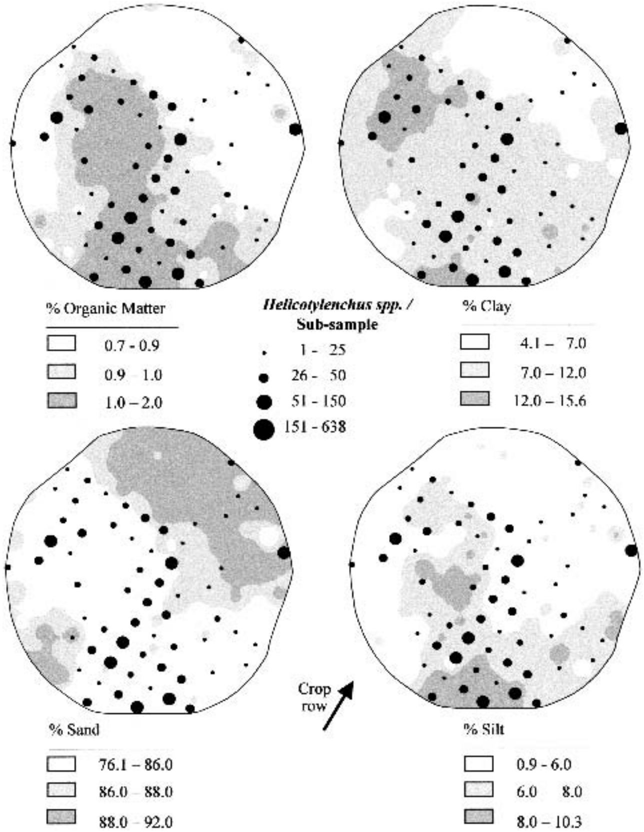

FIG. 7. Sample data for the distribution of *Helicotylenchus* spp. in field 1 in 1997 with interpolated maps for the distributions of organic matter, clay, sand, and silt.

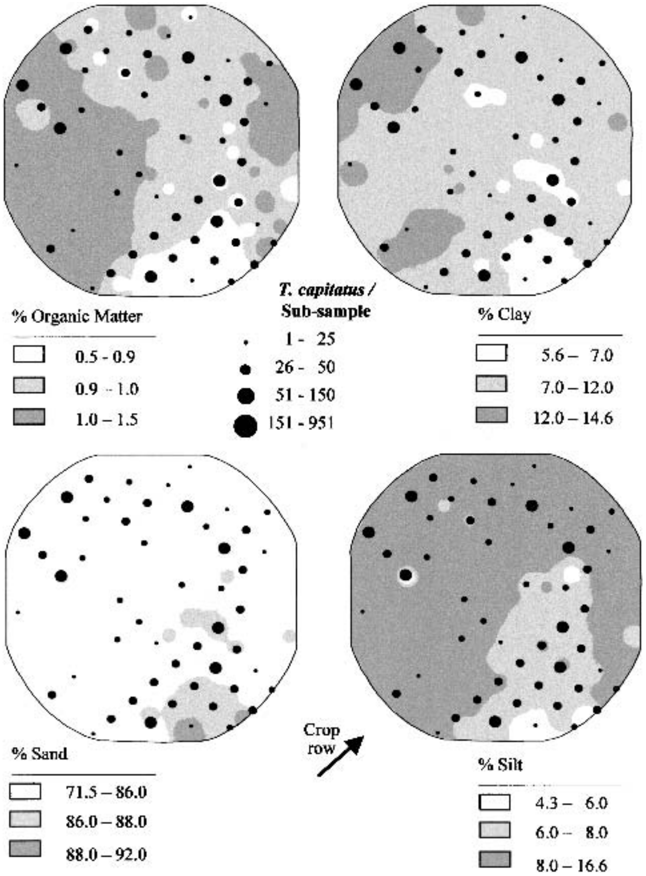

FIG. 8. Sample data for the distribution of *Tylenchorhynchus capitatus* in field 2 in 1997 with interpolated maps for the distributions of organic matter, clay, sand, and silt.

observations in this study (76 m for 0° and 90° from the crop row and 107 m for 45° and 135°). For the 10 samples with spatial dependence, the minimum range of spatial dependence for the four directions investigated was greater than 100 m for all samples and greater than 200 m for half of those samples. Shorter ranges have been previously reported for nematode infestations including 1 to 10 m in old fields and forest landscapes (Gorres et al., 1998), 160 m in a reed canarygrass field (Wallace and Hawkins, 1994), 5 cm to 50 m in a permanent pasture (Marshall et al., 1998), 67 m in a sugarcane crop (Rossi et al., 1996), and 5 to 50 m in agricultural fields in Scotland (Webster and Boag, 1992). No spatial dependence was detected in a corn crop even when distances between paired sampling units ranged from 0.9 to 1,200 m. Ranges may have been longer in this study as a result of both the production system and the size of the fields. The fields were 71 and 53 ha, fairly level, and well irrigated with a center-pivot irrigation system with uniform management within a field.

If the range of spatial dependence of nematode infestations is typically 100 to 200 m, as observed in this study, maps could be made with the scale of soil sampling currently used for variable-rate fertilizer application. For fertilizer application, soil cores are typically collected approximately 100 m apart (Akridge and Whipker, 2000). However, analyzing soil cores for nematodes is more expensive than soil analysis. Accordingly, the benefits will have to be greater for site-specific nematode management than variable-rate fertilizer application. The feasibility of site-specific nematode management will depend on the typical degree of spatial aggregation of nematode infestations and the resulting size of areas within fields that may be left untreated.

Knowledge of typical features of the spatial correlation can lead to the development of guidelines for efficient sampling and mapping (Burrough, 1991). The nature of spatial correlation affects best choice of sample unit, distances between sampling locations, placement of sampling locations (type of grid and orientation), and interpolation method (Burrough, 1991; Flatman et al., 1988; Gotway et al., 1996; Oliver et al., 1997; Weisz et al., 1995). These results indicate that variation in spatial correlation with direction may be a common feature of nematode distributions in center-pivot irrigated fields. Accordingly, investigating anisotropy of nematode distributions could be valuable for recommending methods for sampling and mapping for site-specific management. By adjusting a sampling grid for anticipated anisotropy, fewer observations may be needed or better information about spatial correlation may be obtained with the same number of observations (Flatman et al., 1988). If the anisotropy observed in this study is characteristic for nematode infestations, a rectangular grid would be more efficient for sampling than a square grid. Distances between observations could be greater in the direction of approximately 135° from the crop row than other directions. In addition, an interpolation method that explicitly models spatial correlation to greater distances in the direction of 135° from the crop row than other directions may produce a more accurate map than a method that assumes density is correlated to the same distance in all directions.

The inconsistent correlations of nematode density and soil attributes observed in this study do not support substitution of soil attributes for nematode density when making a map, or the use of soil-attribute maps to specify nematode sampling. Nematode density has been correlated with soil attributes in other studies. Soil bulk density and moisture were significantly correlated with nematode densities at various times of the year for an old field (Gorres et al., 1998) and coarse-textured soils tended to promote reproduction of *Meloidogyne incognita* (Kofoid & White, 1919) Chitwood, whereas *Rotylenchulus reniformis* Linford & Oliveira reproduction was greatest when soil contained moderate levels of clay and silt (Koenning et al., 1996). Noe and Barker (1985) investigated the correlation of three plant-parasitic nematode densities with 26 edaphic variables and found that soil texture also was a useful predictor of nematode densities. Soil attributes such as Mg^{++} have been positively correlated with *Heterodera glycines* Ichinohe cyst and egg densities (Francl, 1993), and organic matter has been associated with the highest densities of *Tylenchulus semipenetrans* Cobb (Marshela et al., 1992).

Correlation between soil attributes and nematode density in this study may have been weaker and less consistent than previous studies because the variation in soil texture and organic matter was small in the fields. Soil texture for both fields was classified as either sand or loamy-sand; percent sand ranged from 71.5% to 92.0%, percent silt ranged from 0.93% to 16.6%, and percent clay ranged from 4.1% to 15.6% within the fields (Figs. 7,8). Organic matter varied only from 0.71% to 2% in the fields (Figs. 7,8). In addition, the observed correlation may be weaker because soil attributes and nematode density were not observed at the same location, but it is unlikely both cores would be collected at the same location for site-specific management. Interpolated values for soil attributes most likely would be used.

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