

## **Delineation of Management Zones for Site Specific Management of Parasitic Nematodes Using Geostatistical Analysis of Measured Field Characteristics**

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### **Abstract**

Delineation of management zones (MZ) for site specific management of cotton-parasitic nematodes requires the study of their spatio-temporal variability, and the identification of surrogate data spatially correlated with their occurrence. The population densities of southern root knot nematodes (RKN) in 11 cotton fields in southern Georgia, USA were measured three times during the growing season in 2005 and 2006. The spatio-temporal variability of the RKN was studied through semivariogram and their spatial correlation with edaphic features through cross-correlograms. Soil electrical conductivity (EC<sub>a</sub>), elevation, slope and the normalized difference vegetation index (NDVI) calculated from a bare soil multispectral image were entered into a canonical correlation analysis to determine which variables explained the greatest amount of variability in RKN population density. Significant edaphic features were entered into a fuzzy clustering algorithm and used to determine the best MZ strategy delineation. The aggregated pattern of RKN at the peak of cotton bloom facilitated the segregation of RKN risk areas based on low values of EC<sub>a</sub> and NDVI. Although this paper presents a summary of the canonical correlation analysis between RKN and edaphic features for the 11 cotton fields, detailed results of the MZ delineation procedure for a single cotton field are presented.

**Keywords:** Southern root-knot nematodes, spatial variability, cross-correlogram, management zones, fuzzy clustering, cotton.

### **Introduction**

Southern root-knot (*Meloidogyne incognita*) and reniform (*Rotylenchulus reniformis*) nematode pressure were the cause of a 3.4 % increase in yield losses across the USA Cotton Belt during the period from 1987 to 2000. Recently, losses of up to 50 % have been reported from individual fields due to the southern root-knot nematode.

Different management strategies such as crop rotation, resistant cultivars and nematicide application have been implemented to avoid yield reduction. However the implementation of some of these strategies should be linked to the spatial and temporal variability of the nematodes. Systematic soil sampling is commonly used to characterize the spatio-temporal distribution of nematodes but this strategy sometimes masks southern root-knot (RKN)

population density variability resulting in missed population patches or clusters (Evans et al., 2002).

The application of uniform rates of nematicide across entire fields to control RKN is the most common management practice among farmers. However, precise application of nematicide only to nematode-infested areas may offer the farmer cost reduction as well as a reduction in environmental impacts. The success of this site specific management (SSM) practice requires a precise characterization of spatial variability in nematode populations, identification of surrogate data related with the spatial distribution of nematodes and the delineation of homogeneous zones requiring similar nematicide rates.

The nematodes spatial distribution has been described as aggregated which is manifested as irregular patches (Goodell and Ferris, 1980) with high occurrence on coarse-textured, sandy soils (Avendaño et al., 2004; Koenning et al., 1996). Geostatistical analyses used by Avendaño et al. (2003) to study the spatio-temporal variability and degree of patchiness of soybean cyst nematodes (SCN) showed a poorly structured spatial variability of these nematodes.

Reflectance from cotton plants in broad and individual spectral bands and vegetation indices have been evaluated as an indirect way to detect the within-field spatial variability of nematode population density (Wheeler and Kaufman, 2003). Avendaño et al. (2003) found that patches of SCN that were not detectable by a geostatistical sampling were detected by remote-sensed images and yield maps. Thus, the identification of surrogate data accounting for a high percentage of the spatial variability of RKN would bring the option of their use for nematode risk zone delineation. The objectives of this study were: (i) to determine the magnitude and extent of spatio-temporal variability in RKN at the field scale; (ii) to establish the relationship between RKN occurrence and the spatial variability of edaphic field features and changes in soil spectral reflectance; and (iii) to develop a methodology for creating RKN management zones.

## Materials and Methods

### Study fields description and data collection

Eleven fields from 8 to 20 ha in size located in an intensely row-cropped region of southern Georgia, USA, were selected for this study in 2005 and 2006. Because of space limitations, a summary of a canonical correlation analysis between RKN and edaphic features for the 11 cotton fields is presented. A detailed discussion of the MZ delineation procedure will be presented for a single field. All fields were planted with the DP555 Boll-Guard<sup>®</sup>, Round-Up-Ready<sup>®</sup> cotton (*Gossypium hirsutum* L.) variety. Discrete data, represented by RKN (*M. incognita*) second stage juveniles, were collected at the center of 0.20 ha square grid cells three times during the growing season: July-August, September, and November. Eight individual subsamples were collected within a 1.5 m radius and combined into a composite sample. The RKN samples were georeferenced using a Trimble AgGPS 114 DGPS receiver. Continuous apparent soil electrical conductivity (EC<sub>a</sub>) data were collected prior to planting using the VERIS<sup>®</sup> 3100 implement. An AgGPS 214 real-time kinematic (RTK) Trimble GPS receiver mounted on the tractor pulling the VERIS<sup>®</sup> 3100 implement was used to collect topographic (elevation) data. This dense data set comprised approximately

7000 points of EC<sub>a</sub> and elevation per field. The normalized difference vegetation index (NDVI) was calculated under bare soil conditions from QuickBird satellite images for all the fields. NDVI was calculated as a normalized difference ratio of near infrared and red reflectance to enhance differences in soil texture. Images were ground-truthed to ensure accuracy.

### Data processing

To match elevation and EC<sub>a</sub> at the RKN sampling locations, continuous surface maps for elevation and EC<sub>a</sub> were created by ordinary punctual kriging using the Geostatistical Analyst extension on ArcVIEW 9.2. Although this procedure tends to smooth the data set, the density of data points used suggests that the impact of estimation at unsampled locations will be minimal. Slope maps were derived from the elevation maps. Polygons or buffer areas of 1.5-m radius were created around each RKN sampling location. Pixel values from the surface maps (EC<sub>a</sub>, elevation, slope) and NDVI within the buffer were averaged and integrated into the analyses.

### Data analysis

The analysis of the data and the results presented are part of a two step process. The first step analyzed the spatial dependence and level of aggregation of the RKN population density through a growing season. The spatial dependence was evaluated using semivariograms. Cross-correlograms were used as one of the two methods to identify surrogate data for RKN management zone delineation. The second step consisted of the use of canonical correlation to identify edaphic and remotely sensed (ED/RS) variables strongly related to the variability in measured RKN data. The delineation of MZ was based on fuzzy clustering of variables having high correlation with the cotton RKN occurrence.

### Geostatistical analysis

When RKN data departed from normality, data were log-transformed. The spatial variability of the RKN population density sampled three times at the CC field during the 2006 cotton growing season was evaluated through experimental semivariograms. If the semivariogram showed an indeterminate increment of semivariance respect to distance, it suggested the presence of a trend or nonstationarity. The presence of a trend in the data set was removed using the restricted maximum likelihood model using SAS (SASInstitute, 2000). This procedure simultaneously estimates the model parameter estimates needed to correct the trend effect and the spatial error parameters. The spatial error parameters were used to calculate the semivariogram of the residuals.

The assessment of spatial structure or spatial dependence was evaluated through the ratio of the nugget (C<sub>0</sub>) over the sill or total variance (C+C<sub>0</sub>). This fraction varies between 0 and 1. Values greater than 0.6 indicate that 60% of the data variability is inexplicable by the model and is associated with short distance random variability. Cross-correlograms were calculated to evaluate the spatial correlation between RKN and ED/RS as one method to identify surrogate data for RKN management zone delineation.

## Statistical analysis

Canonical correlation analysis was used as a second method to measure the strength of association between the ED/RS variables and measured RKN, as well as to select the combination of variables that best explained the largest portion of variability in RKN. Covariates in the data set were identified using the variance inflation factor (VIF) in the PROC REG model procedure in SAS. All variables with  $VIF > 10$  were sequentially removed from the data set prior to the canonical correlation analysis.

Based on the canonical correlation analysis, four different combinations of variables were used to delineate nematode MZs: 1) all contributing variables, 2) two of the variables having the highest correlation with RKN, 3) single variable having a high correlation with RKN, and 4) single variable having a moderate correlation with RKN. Every data set combination was entered into a fuzzy *c*-means algorithm as a surface using the Management Zone Analyst 1.0.1 – MZA software (Fridgen et al., 2004). The number of unique zones created for each data set combination was determined based on the values of normalized classification entropy (NCE) and the fuzziness performance index (FPI), calculated from MZA. Once the zones were identified, a zone was assigned to each RKN observation. The mean and coefficient of variation (CV) of measured RKN within each zone were calculated for comparative purposes of the performance of the *c*-means. Additionally, the mean and coefficient of variation (CV) of the surrogate data were used to characterize each zone, particularly the zone with the highest population density of RKN.

## Results and discussion

### Geostatistical analysis

The semi-variograms calculated for the RKN samples taken from the CC field in August [residuals of  $\text{Log}_{10}(\text{RKN08}+1)$ ] and November [ $\text{Sqrt}(\text{RKN11}+1)$ ] showed a weak spatial structure with values of  $(C_0)/(C_0+C)$  greater than 0.60 (Figure 1). In contrast, the semivariogram from RKN samples taken in early September [residuals of  $\text{Log}_{10}(\text{RKN09}+1)$ ] showed a moderated spatial structure with a value of  $(C_0)/(C_0+C)$  equal to 0.40 (Figure 1). The semi-variograms from August and September showed evidence of periodicity (Figure 1a-1b) indicating the presence of clusters of cotton RKN spatially distributed through the field. The results from the restricted maximum likelihood approach indicated that the range of spatial dependence of RKN sampled in August and September was 159 m and 126 m, respectively (Figure 1a-1b). This range corresponded with small clusters of RKN located on the central and north-eastern part of the field (Figure 2). However, an increase of the semivariance at the distance of 265 m indicated a second range of spatial correlation between the small clusters (Figure 1b). Although the size and the shape of the clusters changed from August to September, the locations of the high RKN population density areas remained stable until the end of the growing season (Figure 2). The spatial dependence observed in the semivariogram from the September RKN samples justifies the use of the raw RKN data sampled in September to evaluate potential surrogate data (ED/RS) for RKN management zone delineation.

A smaller range of spatial variability, 74 m, observed for the RKN sampled in November indicated that the RKN samples from November were spatially independent at distances greater than 74 m. This weak spatial structure, pairs of sample values aligned with the sample variance, observed in Figure 1c was related to small hot spots scattered up to distances of 265 m without a smooth continuity through space (Figure 1c, 2c).

The cross-correlograms calculated from RKN sampled in September indicated differences in spatial correlation with respect to the ED/RS data. Negative spatial correlations between cotton RKN and EC<sub>a</sub>, slope and NDVI are clear in the cross-correlogram (Figure 3). Although elevation showed a strong spatial cross- correlation, elevation did not vary significantly in this field.

The convex shape of the cross-correlogram indicated the strong negative spatial correlation between cotton RKN and Log EC<sub>a</sub>-deep (Kravchenko et al., 2003). The symmetry in the cross-correlogram curves of elevation and Log EC<sub>a</sub>-deep indicated that the spatial correlation of elevation on the cotton RKN was similar in magnitude to the spatial correlation of Log EC<sub>a</sub>-deep but with an opposite sign. This behavior was observed throughout the growing season. A similar relationship for Log EC<sub>a</sub>-shallow and NDVI with cotton RKN also suggests that low NDVI values are associated with coarse textures which have low EC<sub>a</sub> readings.

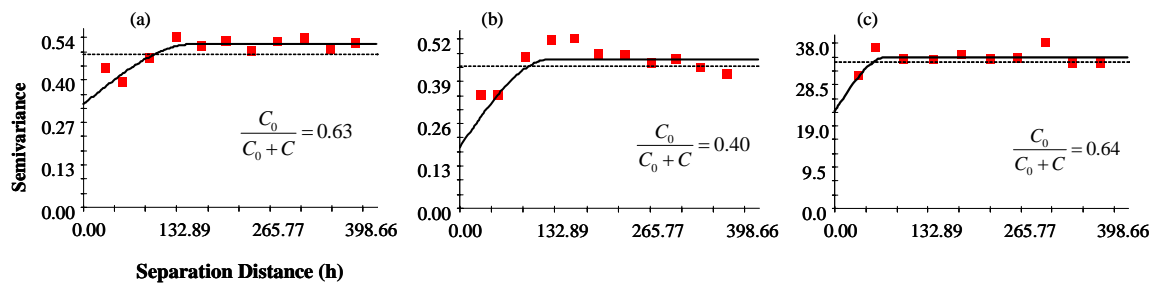


Figure 1. Semi-variograms of cotton RKN sampled in August [residuals of Log<sub>10</sub> (RKN08+1)] (a), September [residuals of Log<sub>10</sub> (RKN09+1)] (b), and November [sqrt(RKN11+1)] (c).

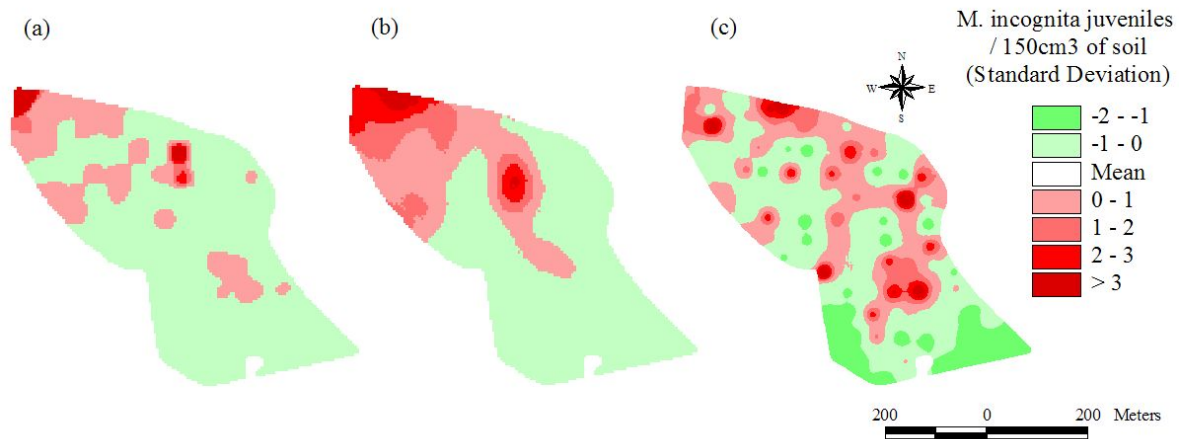


Figure 2. Cotton RKN spatio-temporal distribution evaluated in August (a), September (b), and November (c) at the CC in 2006.

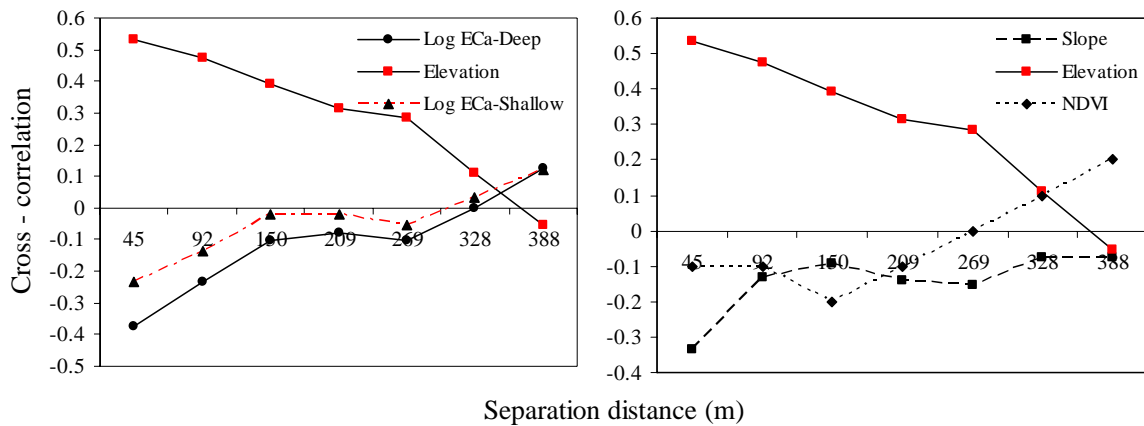


Figure 3. Cross-correlograms for cotton RKN sampled at the CC field in September [Log<sub>10</sub> (RKN09+1)] vs. elevation, Log EC<sub>a</sub>-shallow, Log EC<sub>a</sub>-deep, slope and NDVI.

### Canonical correlation analysis

The canonical correlation analysis was performed with the RKN sampled in July-August because of the high correlation with the ED/RS data that was observed in most of the 11 fields. The canonical correlation analysis showed that EC<sub>a</sub> (shallow and deep) was the variable with the highest correlation to RKN in most of the fields (Table 1).

Although the level of the linear relationship changed from field to field, the correlation indicated that RKN was inversely related with EC<sub>a</sub> in 60 % of the fields. Because low EC<sub>a</sub> values have been related with sandy or coarse-textured soils, the data re-emphasized the fact that nematodes prefer sandy areas in the field (Khalilian et al., 2001). Perry et al. (2006) reported a significant relationship between EC<sub>a</sub> and sand content for the 2005 fields of this study. A positive relationship between topography and EC<sub>a</sub> was found when data from 2005 and 2006 were pooled because of that low-lying areas typically have low values of EC<sub>a</sub> and as a consequence are coarse textured soils. Ortiz et al. (2006) analyzed data pooled across sites in 2005 and found an inverse relationship between elevation and nematodes ( $r = -0.36$ ) which can be related to the re-deposition of sand particles in the low lying areas in which nematodes are mainly found. However, when the relationship was evaluated on a field-by-field basis, this relationship was not very strong. This could be due to the fact that most fields exhibited small changes in topography and slope typical for many sites in the Southern Coastal Plain.

A positive correlation between the NDVI and EC<sub>a</sub> data was observed on 60 % of the 2005-2006 fields. Therefore, low values of NDVI could be associated with high reflectance of coarse textures on the NIR which is characterized by having low values of EC<sub>a</sub> in relation the mean EC<sub>a</sub>. Although the relationship of NDVI calculated from bare soil images and RKN was not consistent between fields, a negative correlation was observed at the RB and CC fields indicating that low values of NDVI were associated with areas of high RKN population density. A similar relationship was observed by Ortiz et al. (2006) when the data from the 2005 were pooled across sites using soil spectral reflectance data extracted

from airplane multispectral images (Table 2). Because of space limitations, only the results from a 20 ha field hereafter referred to as the CC field were selected for detailed presentation in this paper.

Table 1. Results from the canonical correlation analysis between the Log<sub>10</sub> (cotton RKN/150 cm<sup>3</sup> of soil +1) and edaphic - remotely sensed data for each of the studied fields.

	2005					2006					
	Field ID										
	BJ†	BP*	GM*	FR†	PG*	RB†	BJ*	BP‡†	CC†	CMP*	PG†
Eigenvalue	0.70	0.32	0.49	0.52	0.78	0.66	0.17	0.24	0.68	0.50	0.31
Canonical correlation	0.64	0.49	0.58	0.58	0.66	0.63	0.03	0.44	0.64	0.58	0.49
Wilk's Lambda	0.000	0.162	0.014	0.288	0.000	0.000	0.749	0.050	<.0001	<.0001	<.0001
	<b>Correlation coefficients</b>										
Elevation	0.19	-0.06	-0.03	-0.37	0.42	0.48	0.12	0.33	0.61	0.24	0.10
Slope	-0.40	0.19	0.44	-0.29	-0.25	-0.46	-0.06	-0.17	-0.40	0.07	-0.09
EC <sub>a</sub> -Shallow	-0.35	-0.21	0.14	0.35	0.61		-0.02			-0.33	0.39
EC <sub>a</sub> -Deep	-0.22	-0.36	-0.01		0.63	0.48	-0.09	0.07		-0.08	0.40
NDVI	0.06	0.01		0.27	0.15	-0.09		0.25	-0.29	0.37	0.27
Log <sub>10</sub> EC <sub>a</sub> -Deep									-0.47		

† Log<sub>10</sub> RKN collected at flowering stage of cotton.

\* Log<sub>10</sub> RKN collected at harvest.

‡ Normally distributed data

#### Management zone delineation

The results from the canonical correlation analysis and the cross-correlograms indicated that the suitable variables for MZ delineation at the CC field could be: 1) all contributing variables, 2) Log<sub>10</sub>EC<sub>a</sub>-deep and elevation, 3) Log<sub>10</sub>EC<sub>a</sub>-deep, and 4) NDVI. Every data set combination was evaluated to determine the one most appropriate for discrimination between areas with low and high RKN population density.

In general, for each MZ delineation strategy (Table 2) the most homogeneous zone was the one having the highest RKN population density with the lowest CV compared to the whole field (bold font). The variability of Log<sub>10</sub>(RKN09+1) within this zone was reduced by 30 % compared to the whole field. This zone was associated with the lowest EC<sub>a</sub>-deep, slope (%) and NDVI values (Table 2). Data are consistent with previous findings, which have shown that RKN tend to occur at higher densities in sandier soils, which in turn are associated with low EC<sub>a</sub> readings (Khalilian et al., 2001). However, no conclusions could be drawn from the apparent relationship between elevation and RKN distributions due to the flatness of the CC field. Using the data set combination with all contributing variables, only the zone having the highest cotton RKN population density was the most homogeneous, with a within zone RKN CV reduction of 32 %. Elevation and EC<sub>a</sub>-deep were the primary

contributing variables in zone three, having a significantly lower within zone CV compared to the whole field. The data set including all contributing variables was 63% linearly associated with the RKN variability sampled in September (Table 2).

Table 2. Variability of management zones delineated by fuzzy clustering of different combinations of data set at the CC field. Means and coefficient of variation (CV) of different data sets reported for  $\text{Log}_{10}(\text{RKN09}/150 \text{ cm}^3+1)$ , elevation,  $\text{EC}_a$ -deep, slope, and NDVI.

Data Set	No. of zones (n)	$\text{Log}_{10}$ (RKN09/ $150 \text{ cm}^3+1$ )		Elevation (m)		$\text{EC}_a$ -deep (mS/m)		Slope (%)		NDVI		CAN CORR*
		Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	
Elev.-Slope-	1	1.1	73.5	76.2	1.1	1.5	38.8	1.4	19.6	0.09	19.7	0.63
Log $\text{EC}_a$ -	2	1.6	55.2	78.3	1.7	2.5	87.0	2.1	30.2	0.09	23.4	
NDVI	3	<b>1.9</b>	<b>35.0</b>	79.4	0.8	0.7	29.3	0.9	56.6	0.06	37.2	
Log $\text{EC}_a$ -	1	1.0	72.7	76.3	1.2	1.4	32.6	1.4	20.2	0.09	19.9	0.61
deep &	2	1.3	66.6	77.6	1.8	2.9	69.2	1.7	20.3	0.09	15.7	
Elev.	3	<b>2.0</b>	<b>31.9</b>	79.5	0.7	0.7	25.7	1.0	69.8	0.06	37.8	
Log $\text{EC}_a$ -	1	0.8	97.0	76.4	1.8	1.7	19.0	1.5	27.4	0.09	12.1	0.47
deep	2	1.1	72.7	76.7	1.3	4.1	49.4	1.8	18.5	0.11	11.2	
	3	<b>1.7</b>	<b>38.0</b>	78.0	2.0	1.0	14.4	1.3	46.9	0.08	28.3	
	4	<b>2.0</b>	<b>35.0</b>	79.6	0.5	0.6	11.4	0.9	66.2	0.05	31.1	
NDVI	1	1.1	76.7	76.6	2.1	2.1	71.6	1.5	39.4	0.10	15.8	0.29
	2	1.8	39.4	78.8	1.5	0.8	31.5	1.1	48.4	0.07	11.3	
	3	<b>1.9</b>	<b>34.9</b>	79.3	1.0	0.6	23.9	1.1	64.3	0.04	23.0	
Whole field	1	1.6	51.6	78.2	2.2	1.2	89.5	1.2	50.3	0.08	34.8	

\* Canonical correlation

A 61 % of the variability of the data set  $\text{Log}_{10}\text{EC}_a$ -deep and elevation was linearly related with the variability of RKN.

Using the  $\text{Log}_{10}\text{EC}_a$ -deep data set the variability of RKN was linearly associated in a 47 % and the within zone cotton RKN CV was reduced by 29 % on average in zones three and four. Although zones three and four were homogeneous, the mean values of these zones were very similar indicating that maybe the within field variability of the cotton RKN could have been explained with two zones. This also indicates the potential of  $\text{EC}_a$  as surrogate data for RKN management zone delineation.

When the zones were delineated using NDVI, only 29 % of the NDVI variability was linearly associated with the RKN variability. The within zone cotton RKN CV was reduced by 25 % in zones two and three, with 1.9 and 1.8 second stage RKN juveniles per  $150 \text{ cm}^3$  (log transformed values). These zones also reduced the variability in elevation,  $\text{EC}_a$ -deep and slope.

## Conclusions

The strong spatial structure or aggregation of RKN populations, indicated through semi-variograms from samples taken in September probably contributed to the strong correlation between RKN and ED/RS data. The level of aggregation of RKN facilitated the segregation of nematode risk zones for all the different ED/RS data combinations. Our data indicated that RKN susceptible areas may be identified based on soil electrical conductivity (EC<sub>a</sub>) and bare soil reflectance patterns. In all cases, the greatest reduction in RKN variability was associated with the management zone having the greatest risk of infestation. In low-risk areas, the reduction in within zone variability, compared to the whole field, was not as great. This phenomenon is probably due to the random pattern that nematodes exhibit in nature, particularly under conditions common in southern Georgia, USA. Results from this study indicate that RKN management zones using surrogate soil data show great promise for precision management of RKN.

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