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Delineation of Management Zones for Southern Root-Knot Nematode using Fuzzy Clustering of Terrain and Edaphic Field Characteristics

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Management zones (MZs) for southern root-knot nematode (RKN) from the integration of terrain (TR) and edaphic (ED) field features might facilitate variable rate nematicide applications. This study was conducted on 11 coastal plain fields in the USA. The relationships between RKN populations and five soil ED and TR attributes (apparent soil electrical conductivity [shallow ($EC_{a\text{-}s}$) and deep ($EC_{a\text{-}d}$)], elevation (EL), slope (SL), and changes in bare soil reflectance) were analyzed using canonical correlation. Using two ED and TR data sets, canonical predictors were used for zone delineation. Although the results showed that the zones with RKN population above the RKN field average were associated with the lowest values of $EC_{a\text{-}s}$, $EC_{a\text{-}d}$, normalized difference vegetation index (NDVI), and SL with respect to field average values, zone segregation was enough using $EC_{a\text{-}s}$ and $EC_{a\text{-}d}$ data. The results suggest the potential for using soil properties to identify RKN risk zones.

Keywords Apparent soil electrical conductivity (EC_a), cotton, fuzzy clustering, management zones, meloidogyne incognita, precision agriculture, spatial variability, site-specific management, southern root-knot nematodes

Introduction

Site-specific management of southern root-knot nematode [*Meloidogyne incognita* (Kofoid & White) Chitwood] (RKN) could be used for optimization of on-farm resources, reduction of yield loses, and profit maximization. This approach may be useful to target areas at risk for cotton (*Gossypium hirsutum* L.) yield losses associated with nematode parasitism, which has led to yield losses in excess of 10^8 kg across the U.S. cotton belt. In Georgia, the third largest upland cotton producer in the United States (USDA 2008), nematode-related yield losses due to nematodes, 75% associated with RKN, totaled $50.2 million in 2007 (UGA 2007). A survey carried out between 2002 and 2003 (Kemerait et al. 2004; Shurley and Kemerait 2005; UGA 2005) showed that major cotton-producing counties had RKN populations above the recommended threshold [100 second juveniles

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of RKN per 100 cm^3 of soil, Davis et al. (1996)] and estimated that cotton producers lost approximately 77,000 bales of cotton annually as a result (Kemerait et al. 2004).

Plant-parasitic nematodes are found in a variety of soils; however, RKN prefers coarse-textured, sandy soils and occurs in aggregated patches (Starr et al. 1993; Koenning et al. 2004). Pretreatment assessment of RKN populations is commonly made through collection of soil samples; however, high sampling costs restrict the number of samples necessary to make a spatially representative estimation of nematode population densities. Thus, a poor characterization of spatial variability can result in missed population patches, which may reduce the efficacy of nematicide treatments.

The risk of missed nematode population patches could be reduced by delineating management zones (MZs) that characterize the preferred environment of the RKN: coarse-textured, sandy soils. A MZ has been defined as a subregion within a field having a similar combination of yield-limiting and reducing factors for which a single rate of a specific input is appropriate (Doerge 1999). Management zones have been used to study variability in crop yield (Aaron et al. 2004; Jaynes, Colvin, and Kaspar 2005; Xiang et al. 2007) mainly because each zone may indicate different within-field needs, resulting in the implementation of specific management strategies (i.e., variable application of inputs).

Various methods have been proposed to delineate MZs; however, most of them use spatial data that is stable or predictable over time and data related to the phenomena under study. Many studies have shown a strong relationship between nematode population densities and soil properties, therefore suggesting soil features as a tool for MZ delineation. Monfort et al. (2007) explained 65–86% of cotton yield variability using at planting RKN population and percentage of sand fraction. Avendaño et al. (2004) reported a positive correlation between soybean cyst nematode (SCN, *Heterodera glycines*) population density and percentage of sand. Wiatrak et al. (2009) found a strong correlation between the various spatial variabilities of the Columbia lance (*Hoplolaimus Columbus*) nematode and RKN with sandy areas, which were identified by measuring apparent soil electrical conductivity (EC_a). Other research has related abundance of RKN to changes in soil pH (Melakeberhan et al. 2004), soil moisture (Noe and Barker 1985; Wheeler, Barker, and Schneider 1991), and soil physicochemical properties such as clay, organic matter, and low copper concentration (Noe and Barker 1985). Avendaño et al. (2003) found that patches of SCN not detected by a geostatistical sampling were detected by remotely sensed images and yield maps. Similarly, Kulkarni et al. (2008) reported a significant correlation at $P < 0.10$ between SCN population densities at planting and grain yield and the wide dynamic range vegetation index (WDRVI).

In addition to data identification for MZ delineation, several statistical approaches ranging from data selection to data clustering have been implemented. Fraisse, Sudduth, and Kitchen (2001a) used principal component analysis (PCA) to screen out covariates used to define MZs in a clay soil. Partial least squares regression was employed by Bronson et al. (2005) to create new variables extracted from a relationship between soil EC_a and seven soil properties. Canonical correlation analysis (CCA) has been used to study the relationship between soil properties and nematode population densities (Noe and Barker 1985), soil properties and weed populations (Dieleman et al. 2000), and field characteristics and soybean plant performance expressed as yield and canopy development (Martin, Borrero, and Bullock 2005). Data clustering is a key component of the identification of areas with similar edaphic (ED), terrain (TR), and plant growth characteristics and development of MZs (Fraisse, Sudduth, and Kitchen 2001b). The continuous clustering method of fuzzy *c* means is extensively used to analyze soil properties (McBratney and DeGruijter 1992; Tarr et al. 2003; Fridgen et al. 2004), yield (Doberman et al. 2003; Jaynes et al.

2003; Jaynes, Colvin, and Kaspar 2005; Li et al. 2007), and spectral reflectance from plant canopies and bare soil (Boydell and McBratney 2002; Sullivan, Shaw, and Rickman 2005).

The identification of MZs at risk for RKN infestation may allow cotton producers to improve nematode sampling strategies and target variable rate applications (VRAs) of nematicides instead of the more common approach of a uniform rate. Therefore, the overall goal of our research was to develop a methodology for creating RKN MZs. The first objective of this study was to measure the strength of association between soil ED and TR properties and RKN population densities. If a correlation is found, there will be potential for using specific ED and TR properties to delineate RKN MZs. The second objective was to develop a framework of procedures for delineating potential RKN MZs based on the fuzzy clustering of ED-TR properties.

Material and Methods

Study Fields Description and Data Collection

Eleven cotton fields with different soil ED and TR properties located in three counties of southern Georgia (31° 15′ 56.47″ N, −83° 40′ 47.62 E; 31° 32′ 49.78″ N, −83° 23′ 40.12″ E), USA, were selected for this study in 2005 (fields 1–6) and 2006 (fields 7–11). The study areas are largely characterized as floodplains, river terraces, and gently sloping uplands. Bottom lands are nearly level and most valley flanks have less than 5% slope, although some slopes of 5 to 15% exist. The soils are typically sandy to loamy within the first 30 cm of the soil profile (USDA 2002). Table 1 provides a brief description of the fields, including field size (ha), number of nematode sampling locations, and soil taxonomic descriptions. At all sites, cooperating farmers planted the entire field with the Delta & Pine Land Company DP 555 BG/RR cotton cultivar.

Soil Nematode Samples

A 50 × 50 m grid (0.25 ha cell size) was superimposed over each study field, and sampling locations for RKN population density determination were established at the center of each grid. Soil samples were collected three times during the growing season: RKN S1 [75 days after planting (DAP), first square], RKN S2 (110 DAP, flowering), and RKN S3 (167 DAP, harvest). At each grid sampling location, eight individual subsamples were collected within a 1.5-m radius and then composited into a single sample representing average RKN per grid cell. Soil probes with a 3-cm-diameter opening and approximately 20 cm long were used to collect soil samples for nematode population density analysis. Probes were inserted 15–30 cm deep into the soil adjacent to the plant tap root. Each sampling location was georeferenced with a Trimble AgGPS 114 Global Position System (GPS) differentially corrected with the Wide Area Augmentation System (WAAS). This GPS system will be subsequently referred to as DGPS. After each sampling collection, second-stage juveniles, were extracted and counted from a sample of 100 cm^3 of soil by centrifugal flotation (Jenkins 1964).

Apparent Soil Electrical Conductivity and Topography

Because the spatial variability of RKN has been associated with variability in soil texture and TR, continuous EC$_a$ and EL data were evaluated as potential surrogate data for RKN population. EC$_a$ data were collected for each field one time prior to planting. EC$_a$ has been

Table 1
Study locations and soil characteristics, 2005 and 2006

Site ID	County	Field size (ha)	RKN samples	Soil symbol	Soil name	Soil description
1	Tift	11	56	TfB	Tift loamy sand	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults, 2 to 5% slopes
2	Colquit	9	44	Oh	Ocilla loamy sand	Loamy, siliceous, semiactive, thermic Aquic Arenic Paleudults
				Kdb	Kershaw sand	Thermic, uncoated Typic Quartzipsamments, 0 to 5% slope
3	Tift	9	40	Se	Stilson loamy sand	Loamy, siliceous, semiactive, thermic Arenic Plinthic Paleudults
				DoB	Dothan loamy sand	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults, 2 to 5% slopes
				Cn	Clarendon loamy sand	Fine-loamy, siliceous, semiactive, thermic Plinthaquic Paleudults
4	Tift	3	16	DoB	Dothan loamy sand	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults, 2 to 5% slopes
5	Worth	9	48	TfB	Tift loamy sand	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults, 2 to 5% slopes
				FsB	Fuquay loamy sand	Loamy, kaolinitic, thermic Arenic Plinthic Kandiudults, 0 to 5% slopes
6	Tift	9	46	CaB2	Carnegie sandy loam	Fine, kaolinitic, thermic Plinthic Kandiudults, 3 to 5% slopes
				TfB	Tift loamy sand	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults, 2 to 5% slopes
7	Tift	17	67	Dob	Dothan loamy sand	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults, 2 to 5% slopes
				Se	Stilson loamy sand	Loamy, siliceous, semiactive, thermic Arenic Plinthic Paleudults
				Tfb	Tift loamy sand	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults, 2 to 5% slopes
8	Tift	12	48	Tfb	Tift loamy sand	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults, 2 to 5% slopes
				FsB	Fuquay loamy sand	Loamy, kaolinitic, thermic Arenic Plinthic Kandiudults, 0 to 5% slopes
				Pe	Pelham loamy sand	Loamy, siliceous, subactive, thermic Arenic Paleaquults
9	Colquit	20	99	AoA	Albany sand	Loamy, siliceous, subactive, thermic Grossarenic Paleudults, 0 to 2% slope
				Kdb	Kershaw sand	Thermic, uncoated Typic Quartzipsamments, 0 to 5% slope
10	Tift	25	105	Tfb	Tift loamy sand	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults, 2 to 5% slopes
11	Colquit	25	98	FsB	Fuquay loamy sand	Loamy, kaolinitic, thermic Arenic Plinthic Kandiudults, 0 to 5% slopes
				Tfb	Tift loamy sand	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults, 2 to 5% slopes

broadly used as an indirect method to identify changes in soil texture as well as other soil properties such as organic matter and cation exchange capacity (Kitchen, Sudduth, and Drummond 1999; Kitchen et al. 2003; Sudduth et al. 2005). In this study, a Veris 3100 implement (Veris Technologies, Salina, Kan., USA) was used to collect EC_a at two soil depths: 0–30 cm (shallow, $EC_{a\text{-}s}$) and 0–90 cm (deep, $EC_{a\text{-}d}$). An average of 5000 EC_a data points were collected per field by running the implement in 9-m parallel swaths. Every EC_a data point was associated with its corresponding coordinates using a DGPS.

Elevation data (EL) were collected at the same time as EC_a data using a Trimble AgGPS 214 (Trimble, Sunnyvale, Calif.) real-time kinematic (RTK) GPS mounted on the tractor pulling the EC_a implement. The system's base station was located at the edge of the field. Data were recorded at 4-s intervals, which corresponded to approximately 12 m of linear travel.

Remotely Sensed Data

Before the crop was planted, spectral reflectance data of bare soil from QuickBird satellite images were acquired for all fields as an alternative means to evaluate soil texture differences. The QuickBird satellite captures reflectance in four spectral bands: Blue (450 to 520 nm), green (520 to 600 nm), red (630 to 690 nm), and near infrared, NIR (760 to 900 nm). The images were georeferenced and rectified to the universal transverse Mercator projection (UTM), World Geodetic Survey 1984 data (WGS-84), zone 17 north. The pixel size of these images is 2.4 m.

Li et al. (2001) reported high NIR reflectance and low red reflectance on low-lying sandy areas of cotton fields. Based on this, the normalized difference vegetation index (NDVI) was calculated from the multispectral bare soil images to enhance soil texture differences, reduce atmospheric effects and changes in illumination, and reduce the dimensionality of the data. NDVI maps were calculated from the red and NIR bands for all fields using Eq. (1).

$$\text{NDVI} = (\text{NIR} - \text{Red})/(\text{NIR} + \text{Red}) \tag{1}$$

Data Processing

Although the EL and EC_a data sets were composed of an average of 5000 observations per field, the parallel swaths used to collect the data were not necessarily collocated with RKN sampling locations. To overcome this, ordinary punctual kriging was used to estimate the values of EL and EC_a at RKN sampling locations (Kerry and Oliver 2003) using TerraSeer STIS software (Avruskin et al. 2004).

Raster maps of terrain slope (SL) were derived from digital elevation models (DEMs) using the Spatial Analyst extension of ArcVIEW v. 9.0 (ESRI 2004). Using ArcVIEW v. 9.0, polygons or buffer areas of 1.5-m radius were created around each RKN sampling location, and pixel values from SL, EL, NDVI, and EC_a maps within the buffer were extracted, averaged, and integrated with the RKN data for further analyses.

Data Analysis

Statistical Analyses. The departure of RKN data from normality was tested by assessing skewness, the Shapiro–Wilk statistic, and Kolmogorov–Smirnov statistic. The RKN data with skewness values above +1 or below −1 were log-transformed. Descriptive statistics including mean, minimum (Min), maximum (Max), coefficient of variation (CV), and skewness were calculated for all variables.

The canonical correlation analysis (CCA) assesses the relationship between a linear combination of a set of Y variables (RKN data) and a linear combination of a set of X variables (ED-TR properties). This procedure reduces the dimensionality of the data set and maximizes the separability of different clusters while minimizing the variance within each cluster (Johnson and Wichern 2002). Through this method, it is possible to create independent pairs of new variables, canonical variables, where each component of the canonical variable pair is generated from the linear combination of the variables in each group of the original variables (Martin, Borrero, and Bullock 2005). Using data from the 11 fields, CCA was conducted to examine if correlations exist between edaphic (ED)–terrain (TR) properties and RKN population density, as well as to identify ED-TR properties that best explained the largest portion variability in RKN. The level of significance of the canonical correlation was assessed through the Wilks' Lambda statistic. If $P < 0.05$, the pair of canonical variables was significantly associated by canonical correlation. The eigenvalue is the squared canonical correlation and corresponds to the proportion of variance in the canonical predictor variable explained by the canonical correlation relating a pair of canonical variables. The canonical correlation value in this study corresponded to a bivariate correlation between a site canonical variable s_i (linear combination of ED-TR properties) and a RKN canonical variable n_i (RKN data) (Martin, Borrero, and Bullock 2005). The loadings, or correlations in the CCA, indicate the simple linear relation between the original variables and the canonical variable s_i. Variables having a high contribution to the canonical variable s_i are those that exhibit large loadings.

Delineation of RKN Management Zones based on Canonical Predictors of RKN Population. Because of the large number of fields and data collected for this study, three of the largest fields (fields 9, 10, and 11) with different characteristics in respect to the ED-TR properties were selected for RKN MZ delineation. For these fields, the input data for the clustering analysis included canonical predictor variables derived from CCA of different ED-TR properties (Jaynes, Colvin, and Kaspar 2005). Canonical predictor variables were calculated using two strategies of data combination: (1) all the ED-TR properties and (2) two of the properties with the highest structure correlation in the loadings of the site canonical variable $s_{i.}$

Every new canonical predictor variable based in these two strategies was entered into a fuzzy *c*-means algorithm to delineate MZs. The fuzzy *c*-means clustering analysis of predictor variables was chosen to identify MZs composed of ED-TR features having different RKN population densities. Canonical predictor variables for each field and strategy were entered into the Management Zone Analyst software (MZA 1.0.1, USDA-ARS, Columbia, Mo., USA) (Fridgen et al. 2004) for the fuzzy *c*-means clustering analysis. The MZA utilizes the fuzzy *c*-means algorithm and the Euclidean or Mahalanobis distances to separate data into clusters having similar attributes. Postclassification analysis was conducted using two indices generated by MZA: the fuzziness performance index (FPI) and the normalized classification entropy (NCE). The FPI measures the degree of separation (i.e., fuzziness) or membership sharing among a particular fuzzy *c* partition (Odeh, McBratney, and Chittleborough 1992). The FPI ranges goes from 0 to 1, "0" being indicative of distinctive clusters with little membership sharing. The NCE describes the amount of disorganization of a fuzzy *c* partition created by dividing the data into classes (Lark and Stafford 1997). In general, the optimum classification was determined when the FPI and NCE were at minimum with the least number of clusters used (Fridgen et al.

2004). When the results from each index were dissimilar, additional verification was necessary. For example, verification of zone number might be accomplished by comparing the within-zone RKN variation as the number of clusters increases (Fridgen et al. 2004).

Assessing Management Zone Delineation. Ideally, it is expected that the within-field clusters/zones have much lower RKN population variability with respect to the entire field. For each field-MZ delineation strategy, the RKN density mean and coefficient of variation (CV) was calculated per cluster/zone and then compared to the means and CVs of the whole field. This procedure identified differences in the within-field clusters as well as tested the hypothesis of using canonical predictor variables, derived from the relation between RKN population and ED-TR features, to segregate zones with a low or high likelihood of RKN presence.

Delineation of RKN Management Zones based on Edaphic-Terrain Properties. The hypothesis that ED-TR properties can be used to characterize spatial variation in RKN population was fully tested through clustering of the ED-TR data independently of their relation with RKN population. Thus, the raw data of all five ED-TR properties were entered into the MZA software for clustering. The MZ delineation procedure was carried out for fields with significant canonical correlation (fields 1, 3, 5, 6, and 8–11). Next, all georeferenced RKN observations were assigned to each one of the respective MZs. Subsequently, the mean and CV of RKN population densities, as well as the ED-TR properties within each cluster/zone, were calculated. This analysis also contributes to the identification of the ED-TR features closely related with RKN variability, which can be used as potential surrogate data for RKN.

Results

Classical Statistical Analyses

Descriptive statistics of RKN assay results and ED-TR properties for all 11 fields are presented in Table 2. Root-knot population density, second-stage juveniles, varied significantly within and between fields across sampling dates. The mean RKN population density showed an increase from RKN S1 to RKN S2 (approximate midseason), and the distribution was highly skewed (Table 2).

There were both similarities and differences between the ED-TR properties of the 11 fields. The fields exhibited small changes in EL as indicated by the CV (Table 2). In contrast, SL exhibited more variability, especially in fields 1, 3, 10, and 11. The SL at field 10 exhibited a broader range of variation and a high CV even though most of the field exhibited a slope range of 2% to 6%. Low values of EC_a ($EC_{a\text{-}s}$ and $EC_{a\text{-}d}$) and low variability were common for all fields.

Although RKN population densities changed through time, significant correlations between RKN S1 and RKN S2 (i.e., 0.48 and 0.21 for fields 9 and 10, respectively) and between RKN S2 and RKN S3 (i.e. 0.39, 0.56, and 0.22 for fields 9, 10, and 11, respectively) suggest that the spatial distribution of RKN was consistent over the growing season (data not shown).

Canonical Correlation Analyses

For each field, the RKN population density data sampled at RKN S1, RKN S2, or RKN S3 that best correlated with ED-TR properties (data not shown) was used for the CCA.

Table 2
Descriptive statistics of RKN, edaphic, and terrain data for the fields under study, 2005

Factor	Field ID										
	1	2	3	4	5	6	7	8	9	10	11
Mean											
RKN, S1^{ab}	4.8	165.0	0.8	13.4	8.0	39.8	4.6	4.2	43.9	1.6	5.1
RKN, S2^{cb}	156.8	458.3	16.7	208.1	364.3	672.5	83.5	247.7	132.1	64.6	328.3
RKN, S3^{db}	234.0	172.9	23.2	44.6	347.3	242.2	99.6	227.0	116.2	97.3	225.3
EL (m)	109.1	80.9	104.6	121.3	107.0	114.0	105.9	94.7	78.2	107.7	91.9
SL (%)	2.2	0.6	2.2	3.4	4.1	2.9	2.1	2.9	1.2	2.8	1.7
EC$_{\text{a-s}}$ (mS/m)	1.1	0.5	1.1	0.5	2.4	2.4	0.7	1.3	0.9	2.1	0.9
EC$_{\text{a-d}}$ (mS/m)	2.1	0.8	2.3	1.9	4.6	4.9	1.8	2.3	1.2	3.9	1.7
NDVI	0.1	0.3	–	0.2	0.2	0.2	–	0.1	0.1	0.1	0.1
Min.–max.											
RKN, S1^{ab}	0 – 36	0 – 2540	0 – 10	0 – 104	0 – 168	0 – 364	0 – 68	0 – 32	1 – 1281	0 – 52	0 – 60
RKN, S2^{cb}	0 – 580	88 – 1516	0 – 256	0 – 988	2 – 2.820	16 – 2832	0 – 584	16 – 772	1 – 1629	0.88	0 – 1270
RKN, S3^{db}	12 – 920	16 – 488	0 – 184	0 – 428	0 – 1370	0 – 1738	0 – 956	14 – 684	1 – 729	0 – 2006	2 – 1140
EL (m)	106 – 111	80 – 82	101 – 106	119 – 123	100 – 113	111 – 116	102 – 108	92 – 98	74 – 81	103 – 112	88 – 96
SL (%)	0.2 – 6.6	0.1 – 1.2	0.2 – 5.9	2.8 – 4.2	2.8 – 6.1	1.0 – 4.8	0.2 – 3.9	1.2 – 5.4	0.13 – 3.5	0.4 – 14.6	0.6 – 5.5
EC$_{\text{a-s}}$ (mS/m)	0.2 – 4.5	0.06 – 1.5	0.2 – 5.0	0.1 – 1.3	0.1 – 7.2	0.7 – 8.0	0.4 – 1.3	0.4 – 4.4	0.4 – 9.7	0.5 – 9.1	0.3 – 5.6
EC$_{\text{a-d}}$ (mS/m)	0.4 – 6.7	0.07 – 2.5	0.2 – 8.2	0.4 – 3.8	0.4 – 11.4	1.8 – 12.3	0.8 – 3.1	0.4 – 11	0.4 – 7.9	0.7 – 10.4	0.5 – 4.9
NDVI	0.1 – 0.2	0.15 – 1.2	–	0.1 – 0.3	0.1 – 0.2	0.2 – 0.3	–	0 – 0.2	0.02 – 0.2	0.02 – 0.14	0.0 – 0.2

(*Continued*)

Table 2
(Continued)

	Field ID										
Factor	1	2	3	4	5	6	7	8	9	10	11
CV (%)^{e}											
RKN, S1^{ab}	181.9	231.1	300.0	213.8	324.4	178.9	280	190	319.7	395.7	203.2
RKN, S2^{cb}	93.3	65.6	302.9	166.7	173.7	102.8	163	77	171.4	245.3	79
RKN, S3^{db}	79.3	70.1	199.6	238.4	103.3	145.8	174	64	125.5	249.4	75.2
EL (m)^{f}	1.5	0.5	1.3	0.9	3.3	1.4	1.5	1.5	2.1	2.1	2
SL (%)	60.8	38.8	58.4	12.9	18.4	28.7	41	31	50.4	62.9	59
$EC_{a\text{-}s}$ (mS/m)	65.6	55.8	116.9	73.4	79.4	72.0	29	67	117.7	69.9	63.1
$EC_{a\text{-}d}$ (mS/m)	56.0	51.6	90.9	63.0	68.1	47.4	35	98	89.5	52.7	45.7
NDVI	22.4	16.0	–	24.6	14.4	12.9	–	38	34.8	29.9	46.2
Skewness											
RKN, S1^{ab}	2.3	5.9	3.2	2.5	5.5	3.1	3.5	2.4	7.6	5.7	3.0
RKN, S2^{cb}	0.9	1.8	3.6	1.4	2.8	1.5	2.3	0.9	4.3	3.7	1.1
RKN, S3^{db}	1.5	0.9	2.6	3.5	1.1	2.9	2.8	1.0	2.0	5.5	1.7
EL (m)^{f}	−0.2	0.2	−1.0	0.1	−0.1	−0.5	−0.4	0.1	−0.5	−0.1	0.5
SL (%)	1.1	0.7	0.7	0.6	0.4	−0.3	−0.1	0.5	0.6	2.6	1.7
$EC_{a\text{-}s}$ (mS/m)	1.9	1.3	1.9	1.0	0.7	1.9	0.6	1.6	6.6	2.3	5.5
$EC_{a\text{-}d}$ (mS/m)	1.1	2.2	1.4	0.5	0.3	1.5	0.4	2.1	4.0	1.0	1.6
NDVI	0.3	−0.9	–	0.1	−0.2	1.4	–	0.4	0.4	2.2	0.3

[a] Root-knot nematode population (75 days after planting samples).

[b] Second-stage juveniles/100 cm^3 of soil.

[c] Root-knot nematode population (110 days after planting samples).

[d] Root-knot nematode population (167 days after planting samples).

[e] Coefficient of variation, percentage.

Canonical correlation analyses (CCA) between the site canonical variable s_i and the RKN canonical variable were performed individually for the 11 fields. Significant canonical correlations ($P < 0.05$, Wilks' Lambda) were observed in four of the six fields studied in 2005 and four of the five studied fields in 2006 (Table 3). In six of the eight fields with significant canonical correlation, more than 50% of the variability (eigenvalues) in the canonical predictor variable was explained by the canonical correlation between the site canonical variable s_i (strategy one) and the RKN canonical variable n_i.

The properties with high influence on the single canonical predictor variable were those that exhibited large structure coefficients or correlations (Table 3). For the site canonical variable s_i, the properties with the greatest structure coefficients common to all fields were EC_a ($EC_{a\text{-}s}$ or $EC_{a\text{-}d}$), EL, and SL, respectively. Overall, greater coefficients were observed for the ED properties than for the TR properties. Both $EC_{a\text{-}s}$ and $EC_{a\text{-}d}$ made similar contributions in explaining the variability of RKN present in the fields, and their relation was inverse in 60% of the fields (Table 3). A positive correlation between EL and RKN population was observed on six of the eight fields with significant canonical correlation (Table 3). However, this relationship was not very strong because most fields exhibited small changes in elevation, which is typical for the southern coastal plain (Table 2). In contrast, Ortiz et al. (2007) found an inverse relationship between elevation and nematodes ($r = -0.36$) using data pooled from all the 2005 fields. Although the relationship between bare soil NDVI and RKN was not consistent between fields, a negative correlation was observed at field 9, indicating that areas with low values of bare soil NDVI were associated with areas of high RKN population density (Table 3).

Delineation of RKN Management Zones based on Canonical Predictors of RKN Population

The loadings or structure canonical correlations between the site canonical variable s_i and the edapho-terrain properties for fields 9–11 are presented in Table 3. At field 9, the site canonical variable s_i and EL were strongly correlated (0.96); however, this variable was not included in the MZ delineation strategy 2 (only $EC_{a\text{-}d}$ and SL) because of the small changes in terrain observed throughout this field (Table 2). At field 10, the variables of $EC_{a\text{-}s}$, and $EC_{a\text{-}d}$ with the two greatest loadings were used for MZ delineation strategy 2. Finally, at field 11, the two most contributing variables were $EC_{a\text{-}s}$ and NDVI. Therefore, these variables were used to calculate canonical predictors that were later used for MZ delineation.

The results and evaluation of the different MZ delineation strategies for the fields 9, 10, and 11 are presented in Table 4. The evaluation of each MZ delineation strategy was based on the comparison of between-zones mean of nematode population [$\log_{10}$ (RKN / 100 cm^3 of soil $+1$)] and CV with respect to the whole field. Using the CV as an index of dispersion, it was possible to establish the within-field relative variability of RKN population and the field properties. Overall, the zone with the greatest mean nematode population [$\log_{10}$ (RKN / 100 cm^3 of soil $+1$)] had the lowest CV with respect to the CV of the whole field and was different from the zone with the lowest RKN population density.

Strategy 1. Independent of the field, the correlation between the site canonical variable s_i (linear combination of all ED-TR properties) and the RKN canonical variable n_i was more than 48%. When the zones were delineated from this canonical predictor, the variability of the zone with the greatest RKN population density was reduced with respect to the whole field (lowest CV compared to the whole field) (Table 3). For the fields 9, 10, and 11; the

Table 3

Canonical correlation between the pair of canonical variables and structure correlations between the original variables and the canonical variable s_i produced by CCA

	Field ID number										
	2005						2006				
Parameter	1^a	2^b	3^b	4^a	5^b	6^a	7^b	8^{ac}	9^a	10^a	11^b
Eigenvalue	0.70	0.32	0.49	0.52	0.78	0.66	0.17	0.24	0.68	0.31	0.50
Canonical correlation	0.64	0.49	0.58	0.58	0.66	0.63	0.03	0.44	0.64	0.49	0.58
Wilks' Lambda	0.000	0.162*	0.014	0.288*	0.000	0.000	0.749*	0.050	<.0001	<.0001	<.0001
	Structure coefficients or correlations[d]										
Edapho–terrain properties	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
EL[e]	0.30	−0.13	−0.05	−0.64	**0.63**	**−0.76**	**0.67**	**0.76**	**0.96**	0.21	**0.40**
SL[f]	**−0.63**	0.38	**0.75**	−0.50	**−0.38**	**0.73**	**−0.35**	**−0.38**	**−0.63**	−0.18	0.11
$EC_{a\text{-}s}$[g]	**−0.55**	−0.43	0.26	0.60	**0.92**		−0.14			**0.81**	**−0.57**
$EC_{a\text{-}d}$[h]	−0.34	−0.74	−0.02		**0.96**	**−0.77**	**−0.50**	0.16	**−0.53**	**0.83**	−0.14
NDVI[i]	0.09	0.16		0.46	0.23	−0.15		**0.57**	**−0.46**	**0.56**	**0.64**

*No significant correlation between the original variables and the canonical variables.

[a] Canonical variable n_i calculated from $\log_{10}$ RKN S2 data (110 days after planting samples).

[b] Canonical variable n_i calculated from $\log_{10}$ RKN S3 data (167 days after planting).

[c] Normally distributed data. The CCA did not include transformed lognormal data.

[d] Structure coefficients or correlations between the original variables and the canonical variables s_i. Correlations greater than 0.35 are shown in bold font.

[e] Elevation.

[f] Slope.

[g] Apparent soil electrical conductivity shallow (0–30 cm).

[h] Apparent soil electrical conductivity deep (0–30 cm).

[i] Bare soil NDVI.

Table 4

Mean values and variability of RKN population [$\log_{10}$ (RKN/100 cm^3 of soil +1)] within delineated RKN management zones

		Strategy 1		Strategy 2					
		EL-SL-$EC_{a\text{-}d}$-NDVI		$EC_{a\text{-}d}$-SL		$EC_{a\text{-}s}$-$EC_{a\text{-}d}$		$EC_{a\text{-}s}$-NDVI	
Field ID[a]	Zone number[b]	Mean	CV	Mean	CV	Mean	CV	Mean	CV
9	1	0.97	79.9	1.32	70.8	—	—	—	—
	2	1.51	46.6	1.23	66.5	—	—	—	—
	3[c]	2.19	20.8	2.12	20.7	—	—	—	—
	F[d]	**1.58**	**51.6**	—	—	—	—	—	—
	CC[e]	0.63		0.45					
10	1	0.16	300.1	—	—	0.24	282.8	—	—
	2	0.45	176.9	—	—	0.47	171.7	—	—
	3[c]	1.32	71.9	—	—	1.27	74.9	—	—
	F[d]	**0.82**	**117**	—	—	—	—	—	—
	CC[e]	0.48				0.41			
11	1	0.94	69.5	—	—	—	—	0.94	69.5
	2	2.09	14.7	—	—	—	—	2.11	14.9
	3[c]	2.37	13.5	—	—	—	—	2.37	14.3
	4[c]	2.35	16.6	—	—	—	—	—	—
	F[d]	**2.21**	**17.9**	—	—	—	—	—	—
	CC[e]	0.58						0.56	

[a] Data set used to calculate an edaphic-terrain canonical variable.

[b] Data in parentheses show the number of observations per zone.

[c] Zone classified as RKN prone.

[d] Field average and coefficient of variation are in bold font.

[e] Canonical correlation between the site canonical variable s_i and the RKN canonical variable.

variability of RKN population within this zone (zone 3 and zone 4 on the field 11) was reduced by 59%, 38%, and 7% respectively compared to the whole field.

For fields 9 and 10, the RKN-prone zone—zone 3—has lower $EC_{a\text{-}s}$ ($\leq$1.27 mS m^{-1} for field 10) and $EC_{a\text{-}d}$ ($\leq$0.60 mS m^{-1} and $\leq$2.49 mS m^{-1} for fields 9 and 10, respectively) mean values with respect to the whole-field mean value (Table 2) as well as mean values for zones 1 and 2 (data no shown). At field 9, soil samples randomly collected at a depth of 0–90 cm within this zone showed that soil was composed of more than 93% sand, 3% clay, and 4% silt. A sand fraction analysis showed that 55% of the sand in this area had particle size in a range of 0.25 to 2 mm. Therefore, the low values of EC_a can be related to an increase in coarse sand in the $\geq$ 0.25-mm range. Similarly, soil samples randomly collected at a depth of 0–30 cm within zone 3 of field 10 showed that soil was composed of 92% sand, 2% clay, and 5% silt. Zone 3 in fields 9 and 10 was also characterized by the lowest mean values of SL ($\leq$0.7%, field 9), and NDVI ($\leq$0.06, field 9, and $\leq$0.05, field 10) compared to zones 1 and 2 as well as the whole-field mean (Table 2). A map of field 9 depicting the three MZs delineated using strategy 1 is shown in Figure 1(a). This map illustrates good spatial distinction of zones with different levels of RKN population density. The MZ map also has similarities with spatial patterns in the $EC_{a\text{-}d}$ map [Figure 1(f)], which

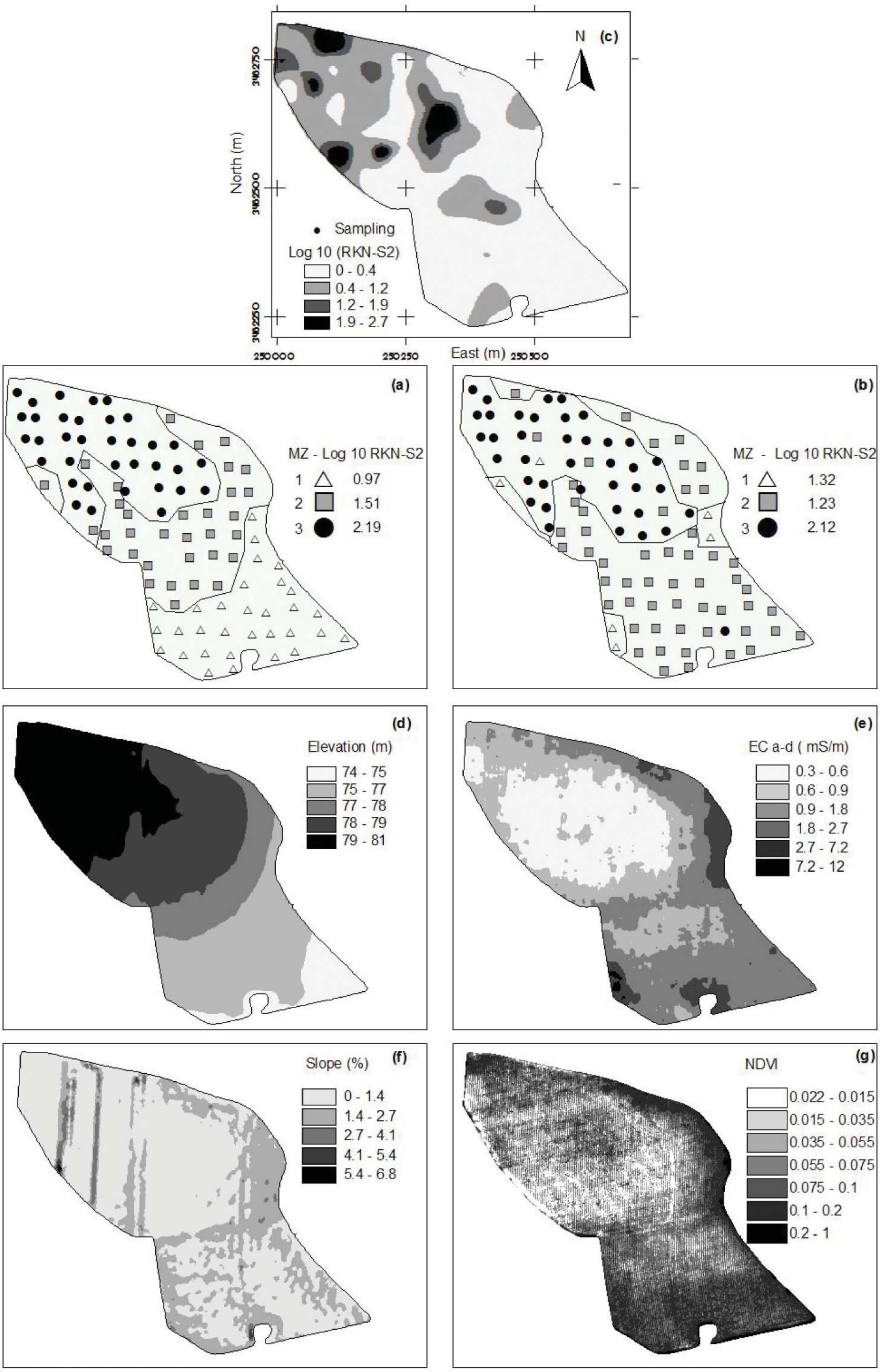

Figure 1. Root knot nematode (RKN) management zones (MZ). Delineated from (a) strategy 1 and (b) strategy 2: canonical correlation between (b) RKN population density (RKNS2) and edapho-properties: (d) elevation, (e) $EC_{a\text{-}d}$, (f) slope, and (g) NDVI.

reaffirms the impact of this variable on the segregation of zones having high and low risk for RKN occurrence.

Contrasting with zone 3, in fields 9, 10, and 11, the RKN variability in zone 1 with the lowest RKN population density was not reduced with respect to the whole field. This zone was mainly characterized by the higher $EC_{a\text{-}d}$ and NDVI mean values than zones 2 and 3. The mean $EC_{a\text{-}d}$ values within this zone (2.0 mS m^{-1} and 7.66 mS m^{-1} for fields 9 and 10) increased 70% and 96% respectively with respect to the mean $EC_{a\text{-}d}$ of each field. Different from zone 3, this zone on field 9 was composed of 89% sand, 2% clay, and 9% silt, and 49% of the sand particles were between 0.106 and 0.044 mm. The increase in silt percentage and decrease in sand particle size as well as the increase in slope may be related with the decrease in RKN population density and an increase in soil moisture. Increases in soil water matric pressure and soil moisture associated with increases in fine soil particle-size classes have been reported as detrimental for nematode reproduction, hatching, and movement (Koenning and Barker 1995). The mean NDVI within zone 1 field 9 (0.10) increased 66% with respect to the mean NDVI of zone 3 (0.06) and 25% with respect to the mean NDVI of the whole field (data not shown). The high values of NDVI in zone 1 may indicate a darker soil with an increase in soil moisture, which might be related to the increase in fine particles where nematodes seem to be less prone. Similar to field 9, zone 1 and 2 on field 10 had the highest $EC_{a\text{-}s}$, $EC_{a\text{-}d}$, and NDVI mean values compared to mean values for the field (data not shown). The high mean values of $EC_{a\text{-}s}$, $EC_{a\text{-}d}$, and NDVI in zone 2 can be related with the increase in clay (12%) and silt (11%) and a decrease in sand content (67%) compared with zone 3.

The fuzzy clustering procedure for delineation of MZ on field 11 did not show significant differences between zones: differences in RKN population as well as field features. Although fuzzy clustering analysis divided the canonical predictor into four zones, there were zones with similar RKN population density as well as ED-TR features. For example, zones 3 and 4 were similar with respect to RKN population, EL and $EC_{a\text{-}s}$, but different with respect to $EC_{a\text{-}d}$, SL, and NDVI (data not shown). The canonical correlation indicated that $EC_{a\text{-}s}$ was the variable most highly correlated with RKN population density. However, zones 2–4 had similar average $EC_{a\text{-}s}$ which may be associated with the low within-field variability of the RKN population density. Moreover, when a semivariogram of RKN-S3 (used for the CCA) was calculated, a pure nugget effect (0.16) was found. Therefore, this low spatial variability was one of the factors conducive to a poor distinction of areas with low and high RKN population density, making difficult the process of identification of "RKN-prone zones" and surrogate data for RKN MZ delineation.

Strategy 2. Although the zones were delineated from a canonical predictor derived from a small data set, only two variables were used to calculate the site canonical variable s_i, and the variability of the zone with the greatest RKN population density was reduced with respect to the whole field (lowest CV compared to the whole field) (Table 3). By using this MZ delineation strategy, the correlation between the site canonical variable s_i (linear combination of all ED-TR properties) and the RKN canonical variable n_i was around 45%, and it was not considerably reduced with respect to the strategy one. Basing the delineation of RKN MZ on the combination of this small data set resulted in fields 9–11 having similar within-zone RKN population to the one observed with the strategy 1. This indicates that some of the ED-TR properties, EL and bare NDVI with low CV values (Table 2), included in the strategy 1 exhibited low spatial variability and therefore had a low contribution to the MZ delineation. For the fields 9 [Fig. 1(c)], 10, and 11, the variability of RKN population within this zone (zone 3) was reduced by 60%, 36%, and 20% respectively compared to the whole field. The variability in soil $EC_{a\text{-}s}$ within this zone was reduced 61% ($EC_{a\text{-}d}$), 55%, and 58% for fields 9, 10, and 11, respectively, with respect to the whole field (data not shown). A map of field 9 depicting the three MZs delineated using this strategy is shown in Fig. 1(c). This map shows that zone 3, the highest risk for RKN occurrence, resembles the area with the greatest RKN population density in Fig. 1(b). The random pattern followed by the few locations assigned to zone 1 explains the high variability in RKN population and $EC_{a\text{-}d}$.

Similar to the strategy 1, the RKN variability in zone 1 with the lowest RKN population density was not reduced with respect to the whole field. This zone was mainly characterized by higher $EC_{a\text{-}s}$ or $EC_{a\text{-}d}$ mean values than zones 2 and 3. The mean EC_a values within this zone (3.59 mS m^{-1}, 6.11 mS m^{-1}, and 4.11 mS m^{-1} for fields 9, 10, and 11, respectively) increased 220%, 188%, and 334.4% for fields 9, 10, and 11, respectively, with respect to the whole-field mean of EC_a (data no shown).

At field 11, although the clustering analysis resulting from MZ delineation strategy 2 suggested three MZs, there were similarities in within-zone RKN population, which suggests that two zones will be enough to discriminate RKN population variability and risk areas.

Delineation of RKN Management Zones based on Edaphic-Terrain Properties

The results from fuzzy clustering of ED-TR properties showed that it was possible to differentiate a zone with the greatest RKN population (lowest CV with respect to the CV for the whole field) from any other areas or zones within each of the studied fields (Table 5). Zone 3 for the fields 1, 6, and 10 as well as zone 4 for the fields 3, 5, 8, and 9 had the greatest RKN population with respect to the whole-field mean. The percentage increases in RKN population within this zone respect to the whole-field RKN mean were 33%, 360%, 78%, 58%, 18%, 51%, and 15% for the fields 1, 3, 5, 6, 8, 9, and 10 respectively. In contrast, the percentage reductions in RKN population within this zone respect to the whole-field RKN mean were 25%, 70%, 59%, 26%, 14%, 23%, and 7% for the fields 1, 3, 5, 6, 8, 9, and 10 respectively. This zone consistently had low $EC_{a\text{-}s}$ and $EC_{a\text{-}d}$ values compared to the whole-field mean. In contrast, the characteristics of this zone with respect to EL, SL, and NDVI change from field to field. For the same fields, the reduction in $EC_{a\text{-}d}$ values within that zone with respect to the whole-field $EC_{a\text{-}d}$ mean was 14%, 69%, 74%, 22%, 34%, 42%, and 23%, respectively (Table 5). Slope has the next greatest additional ability to segregate RKN prone areas across all sites after $EC_{a\text{-}d}$. Low values of SL compared to the whole-field mean were observed for the fields 1, 8, and 9. The reduction in SL values within that zone with respect to the whole-field SL mean was 41%, 17%, and 42% for fields 1, 8, and 9, respectively. For the field 11, similar to the results from MZ delineated based on canonical predictors, there were not significant differences in RKN population between the zones delineated based on ED-TR properties.

Zone 1 has low RKN population compared to the average value of each field and the other zones. The percentage reductions in RKN population for this zone with respect to the whole-field RKN means were 60%, 78%, 79%, 62%, 60%, 74%, 20%, and 32% for the fields 1, 3, 5, 6, 8, 9, 10, and 11, respectively. In some fields, zone 1 was characterized by greater $EC_{a\text{-}s}$ and/or $EC_{a\text{-}d}$ values compared to the $EC_{a\text{-}s}$ and/or $EC_{a\text{-}d}$ values of the zones having the greatest RKN population density. The percentage increases in $EC_{a\text{-}d}$ within this zone respect to the whole-field mean of $EC_{a\text{-}d}$ were 64%, 31%, 16%, and 59% for the fields 5, 6, 9, and 10, respectively. High values of SL with respect to the mean of the whole field described zone 1 at the fields 1 and 8. The patterns of variation of EL, and bare NDVI

Table 5

Management zone delineation based on edaphic-terrain data tested on nine fields located in the southeastern coastal plain (management zones delineated from fuzzy clustering of edaphic and terrain variables)

		Variables[d]											
Field ID[a]	Zone number[b]	RKN[c]		EL		SL		$EC_{a\text{-}s}$		$EC_{a\text{-}d}$		NDVI	
		Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	1 (13)	62	108	109	1.47	3.0	48.3	0.7	162.3	1.3	128.5	0.10	12.8
	2 (19)	158	100	108	0.97	2.3	46.0	1.5	34.7	2.8	21.2	0.15	17.1
	3 (23)	211	69	110	0.90	1.3	58.3	1.0	48.9	1.8	38.8	0.14	20.1
	F[e]	**158**	**92**	**109**	**1.94**	**2.2**	**61.0**	**1.1**	**69.7**	**2.1**	**56.0**	**0.13**	**0.2**
3	1 (21)	5	165	105	0.41	1.4	50.7	0.5	78.2	1.5	75.0		
	2 (4)	16	105	104	0.54	3.7	22.9	3.5	34.0	7.1	11.0		
	3 (10)	23	220	103	0.97	2.7	23.3	1.1	135.0	2.8	46.0		
	4 (5)	106	60	106	0.53	3.6	56.0	0.3	29.0	0.7	85.0		
	F[e]	**23**	**200**	**105**	**1.32**	**2.2**	**58.0**	**1.0**	**129.0**	**2.3**	**91.0**		
5	1 (12)	61	206	111	0.78	3.5	11.1	4.5	32.0	7.7	23.0	0.17	5.7
	2 (12)	212	100	106	2.46	4.8	12.0	2.7	53.0	6.4	41.0	0.17	11.0
	3 (6)	253	92.4	102	0.6	4.4	16.7	1.8	40.0	2.9	59.0	0.20	7.7
	4 (14)	509	42	105	1.78	4.0	18.0	0.5	40.0	1.2	60.0	0.14	9.1
	F[e]	**286**	**103**	**106**	**3.28**	**4.1**	**18.4**	**2.4**	**79.3**	**4.7**	**68.0**	**0.17**	**14.2**
6	1 (14)	253	115.7	115	0.63	1.9	41.4	3.3	73.0	6.4	50.5	0.18	7.2
	2 (13)	584	93.8	115	0.55	3.5	18.6	2.2	37.2	4.8	25.1	0.19	3.5
	3 (19)	1062	77.3	112	0.97	3.0	11.4	2.0	82.0	3.8	36.1	0.20	17.4
	F[e]	**673**	**104**	**114**	**1.38**	**2.9**	**29.0**	**2.5**	**72.6**	**4.9**	**47.4**	**0.19**	**12.4**

(*Continued*)

Table 5
(Continued)

Field ID[a]	Zone number[b]	Variables[d]											
		RKN[c]		EL		SL		$EC_{a\text{-}s}$		$EC_{a\text{-}d}$		NDVI	
		Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
8	1 (6)	98	68.7	93.4	1.01	3.5	45.1	1.5	44.6	2.0	82.3	0.03	39.1
	2 (5)	162	71.8	93.7	0.48	3.4	19.6	3.2	28.4	7.7	30.1	0.12	33.2
	3 (11)	217	70.9	93.6	0.8	3.7	14.3	1.0	46.7	1.6	60.7	0.09	23.2
	4 (26)	293	66.5	95.7	1.06	2.4	24.5	1.0	49.0	1.5	63.0	0.08	21.1
	F[e]	**248**	**77.4**	**94.7**	**1.48**	**2.9**	**31.4**	**1.3**	**66.8**	**2.3**	**97.8**	**0.08**	**37.5**
9	1 (32)	34	189.5	76.2	1.17	1.4	19.9	0.9	34.6	1.4	35.1	0.09	20.2
	2 (7)	79	130.7	77.0	1.36	1.8	16.8	3.5	88.5	4.0	52.4	0.10	10.1
	3 (17)	167	178.6	79.2	0.90	1.9	30.4	0.7	34.1	0.8	41.9	0.06	38.0
	4 (43)	198	132.5	79.5	0.77	0.7	48.4	0.6	21.5	0.7	29.4	0.06	36.9
	F[e]	**131**	**172.7**	**78.2**	**2.15**	**1.2**	**50.3**	**0.9**	**117.7**	**1.2**	**89.5**	**0.08**	**34.8**
10	1 (17)	52	340.6	107.3	1.75	5.0	66.1	3.7	54.0	6.2	40.9	0.04	27.9
	2 (47)	60	236.6	106.0	1.32	2.6	42.7	2.0	54.5	3.9	44.5	0.06	28.1
	3 (41)	75	228.1	109.9	1.17	3.0	43.1	1.7	74.8	3.0	48.1	0.05	23.9
	F[e]	**65**	**245.3**	**107.7**	**2.13**	**3.1**	**59.5**	**2.1**	**69.9**	**3.9**	**52.7**	**0.05**	**29.9**
11	1 (35)	153	67.6	91.3	0.76	1.3	37.9	0.7	28.1	1.5	35.1	0.04	27.6
	2 (5)	204	87.3	91.3	1.40	4.4	19.2	0.9	98.0	1.1	60.3	0.06	34.6
	3 (26)	243	96.2	91.3	1.36	1.3	42.1	1.1	92.7	1.4	56.2	0.08	23.6
	4 (23)	276	46.7	94.5	1.08	1.6	29.6	1.0	16.2	1.9	29.3	0.09	14.6
	5 (9)	336	47.3	89.6	1.10	3.3	19.2	1.3	33.8	2.7	33.6	0.11	32.4
	F[e]	**225**	**75.2**	**91.9**	**1.98**	**1.7**	**59.0**	**0.9**	**63.1**	**1.7**	**45.7**	**0.07**	**46.2**

[a] Field identification number.

[b] Data in parentheses show the number of observations per zone.

[c] RKN population density per zones (second stage juveniles per 100 cm^3 soil).

[d] Set of edaphic and terrain variables used for the management zones delineation.

[e] Field average and coefficient of variation are in bold font.

were not very consistent across the fields compared to soil EC_a and SL. For some fields, however, the zone with the greatest RKN population (zone 3 or 4) was characterized by low or high EL and bare NDVI mean values. This may indicate a low within-field spatial variability of EL and/or bare NDVI, which could result in a low contribution of these variables to the MZ delineation.

Overall, there were similarities between the zones with respect to the average values of RKN population as well as the ED-TR properties. For example, four zones were delineated for fields 5, 8, and 9 after the fuzzy clustering analysis; however zones 2 and 3 field 5, zones 1 and 2 field 8, and zones 3 and 4 field 9 had similar mean values of RKN population, EL SL, and EC_a; therefore the overall number of zones delineated for these fields could be even reduced to two zones in most cases. The results presented in Table 5 agreed with the MZ delineated based on canonical predictors suggesting that the ED-TR properties can be used to segregate areas having high and low risk for high RKN population density, and data from $EC_{a\text{-}s}$ and $EC_{a\text{-}d}$ provide enough level of detail to characterize those RKN risk levels.

Discussion

Although RKN population aggregates in patches or irregular clusters within cotton fields, this pattern of variability might be related to specific field features, which can be used as means to segregate areas at risk for high population. The key is, therefore, the identification of those field features and the type of spatial correlation with RKN population.

Various approaches have been evaluated to identify relations between various sets of variables. However, CCA has shown promising results in the study of the relationship between soil properties and nematode population densities (Noe and Barker 1985), soil properties and weed populations (Dieleman et al. 2000), and field characteristics and soybean plant performance expressed as yield and canopy development (Martin, Borrero, and Bullock 2005).

In this study, CCA allowed us to identify the relation between RKN population and field features that can be used to generate canonical variables, which can predict up to 50% of RKN variability. This predictive level was mainly explained by the inverse relation of both $EC_{a\text{-}s}$ and $EC_{a\text{-}d}$ with the RKN population present, which has been defined by various studies as soil texture mediated. Wiatrak et al. (2009) associated low EC_a values with sandy or coarse-textured soils. Wolcott et al. (2004), pooling data from cotton fields collected in 2001 and 2002, reported a positive correlation (0.94) between clay content and EC_a. They reported that damaging levels (>250 nematodes per cm^3 of soil, Louisiana threshold) of nematodes were only observed in EC_a zones that contained 15% or less clay content. Therefore, the negative correlation between EC_a and the RKN population shown by the CCA reaffirmed that nematodes prefer areas with low values of EC_a, which are associated with coarse-textured soils. Perry et al. (2006) reported an inverse relationship between EC_a and sand content for the 2005 fields included in this study. Data from the 2006 fields showed a negative correlation between EC_a and increasing soil particle size [from medium (0.25 mm) to coarse (2 mm)] and a positive correlation with decreasing particle size (medium to fine). This shows the sensitivity of EC_a for segregating areas of different soil particle size.

Besides the correlation between EC_a and RKN, other ED variables or data representing changes in ED properties were related to RKN population. The positive correlation between EL and RKN population observed on six of the studied fields (Table 3) could be explained through the positive correlation between elevation and EC_a found when 2005 and 2006 data were pooled. On coastal plain low-lying areas where those fields were located, the result of erosion deposition are coarser textured soils where nematodes are prone. The negative correlation between bare soil NDVI and RKN (field 9), although not consistent between fields, indicates that areas with low values of bare soil NDVI might be associated with areas of high RKN population density (Table 3). A similar relationship was observed by Ortiz et al. (2007) using data from the 2005 fields. The coarser sandy areas with low values of EC_a in the studied fields exhibited lower NDVI values than the finer sandy soils or soils with increased clay content. Because the soils in the southern coastal plain are mainly sandy, soil spectral reflectance in the NIR band is greater than the red band. However, smaller differences in soil spectral reflectance between these two bands were found in the coarser sandy areas than in the finer sandy areas. Similarly, Li et al. (2001) found that low-lying areas with sand content greater than 740–828 g kg^{-1} in the first 30 cm of depth had high reflectance in the NIR and low reflectance in the red and middle infrared (MIR). Sullivan, Shaw, and Rickman (2005) found a negative correlation between clay content and red (630 to 690 nm) and NIR (760 to 900 nm) reflectance on soils from the Tennessee Valley and coastal plain of Alabama. They also found that visible and NIR reflectance increased as the clay content in the soil decreased.

The evaluation of RKN MZ delineation based on canonical predictors of RKN population evidenced the power of the ED-TR properties for segregating areas having high and low risk for high RKN population density but more importantly to differentiate areas prone to high RKN population. Soil EC_a ($EC_{a\text{-}s}$ or $EC_{a\text{-}d}$) was the common variable to all field-zone delineations which evidenced the high contribution of soil texture, expressed by the changes in $EC_{a\text{-}s}$ and $EC_{a\text{-}d}$ to the discrimination of areas at risk for RKN population occurrence. Previous studies have also shown that RKNs tend to occur at greater densities in sandier soils, which in turn are associated with low EC_a readings (Wolcott et al. 2004; Monfort et al. 2007; Wiatrak et al. 2009). When the zones were delineated from ED-TR properties independently of their relation with RKN population, it was possible to differentiate a zone with the greatest RKN population from any other areas or zones within each of the studied fields. The characteristics of this zone with respect to EL, SL, and NDVI change from field to field; however, this zone consistently had low $EC_{a\text{-}s}$ and $EC_{a\text{-}d}$ values compared to the whole field mean, which reaffirms that EC_a provides enough level of detail to identify zones with different RKN risk levels. Therefore, it has potential as surrogate data for RKN MZ delineation.

Although the discrimination of zones with different levels of risk for RKN occurrence has been viewed as the differentiation among sand, clay, and silt areas within a field, with sandy areas having the greatest risk, this strong differentiation is not exhibited by the southern coastal plain soils. Fields planted with row crops do not exhibit high variability in soil textural classes. In contrast, the soils are characterized by coarse-sandy textures. Therefore, the differentiation of the zones at risk for nematode occurrence must be based on the segregation of sandy areas with different particle size. Similar conclusions were reached by Monfort et al. (2007). The on-the-go sensing of EC_a throughout a field brings an alternative for the discrimination of areas with differences in soil texture and particle size. A correlation analysis between sand fraction data and EC_a supported the hypothesis that EC_a (EC_a or $EC_{a\text{-}d}$) is sensitive to changes in particle size with $EC_{a\text{-}d}$ being more sensitive.

It is also important to mention that fields with low variability of the RKN population density (field 11) and the random pattern of the locations with high RKN population could made the identification of ED-TR features associated with RKN occurrence very complex. The conditions observed in field 11, for example, illustrate the difficulties of delineating MZ for site-specific RKN management when the RKN population density is not highly structured and there is not enough within-field variability of field features.

Conclusions

The results from this research showed that zones with high and low risk for RKN population occurrence can be delineated using ED and TR properties. The MZ delineated for the fields included in this study had both similarities and differences with respect to the variability in RKN population density as well as the ED-TR properties, which can be viewed as different scenarios faced by the cotton producers. The comparison of the two strategies for MZ delineation based on canonical predictors and the zones delineated based on raw ED-TR data showed that segregation of areas or zones with high and low population of nematodes is possible through the use of ED-TR data and most important that a reduced data set can be used for those purposes.

The analysis of the results indicated that areas likely to have high levels of RKN population might be mainly identified through the within-field changes in EC_a ($EC_{a\text{-}s}$ or $EC_{a\text{-}d}$). However, if the field exhibits significant variability in TR properties, flat areas will be more likely to have high RKN levels.

For most of the fields, the variability within the zone with the greatest RKN population (high risk zone) was reduced with respect to the whole field (the lowest CV with respect to the whole field) and this zone was characterized by the lowest mean values of $EC_{a\text{-}s}$, $EC_{a\text{-}d}$, NDVI, and SL. In contrast, the zone with the lowest RKN population density (low-risk zone) exhibited the greatest values of $EC_{a\text{-}s}$, $EC_{a\text{-}d}$, NDVI, and SL with respect to the average values of the field. This zone also did not have a significant reduction in RKN variability compared to the whole field. This phenomenon was likely due to the random pattern that nematodes exhibit in nature, particularly under conditions in southern coastal plain soils.

When EC_a ($EC_{a\text{-}s}$ or $EC_{a\text{-}d}$) was evaluated for MZ delineation, significant differences between zones with high and low RKN population density were observed. This shows the potential for EC_a to serve as surrogate data for RKN MZ delineation. The positive correlation between EC_a and NDVI calculated at bare soil conditions and the significant differentiation of RKN risk areas suggested that NDVI also can be used as surrogate data for RKN. Although this type of data alone did not provide strong discrimination of the areas with a high likelihood for having a high RKN population, the differentiation of MZ improved when NDVI and $EC_{a\text{-}s}$ or $EC_{a\text{-}d}$ were combined. The validation results of the RKN MZ delineation reaffirmed that the $EC_{a\text{-}s}$ and $EC_{a\text{-}d}$ properties offer much more detail to characterize areas with low and high risk for having high RKN population.

Results from this study indicate that RKN MZ delineated from surrogate ED data can facilitate the site-specific management of RKN, especially the site-specific application of nematicides. The results also showed that if there is neither structured within-field spatial variability for RKN population nor ED or TR properties, no discrimination by MZs is recommended.

In conclusion, the RKN MZ approach presented in this study can be used to decide various threshold values, which might bring the opportunity for implementing within field variable rate application of nematicides.

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