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Variable Rate Application of Nematicides on Cotton Fields: A Promising Site-Specific Management Strategy

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Abstract: Field tests were conducted to determine if differences in response to nematicide application (i.e., root-knot nematode (RKN) populations, cotton yield, and profitability) occurred among RKN management zones (MZ). The MZ were delineated using fuzzy clustering of five terrain (TR) and edaphic (ED) field features related to soil texture: apparent soil electrical conductivity shallow ($EC_{a\text{-shallow}}$) and deep ($EC_{a\text{-deep}}$), elevation (EL), slope (SL), and changes in bare soil reflectance. Zones with lowest mean values of $EC_{a\text{- shallow}}$, $EC_{a\text{- deep}}$, NDVI, and SL were designated as at greater risk for high RKN levels. Nematicide-treated plots (4 rows wide and 30 m long) were established in a randomized complete block design within each zone, but the number of replications in each zone varied from four to six depending on the size of the zone.The nematicides aldicarb (Temik 15 G) and 1,3-dichloropropene (1,3-D,Telone II) were applied at two rates (0.51 and 1.0 kg a.i./ha for aldicarb, and 33.1 and 66.2 kg a.i./ha for 1,3-D) to RKN MZ in commercial fields between 2007 and 2009. A consolidated analysis over the entire season showed that regardless of the zone, there were not differences between aldicarb rates and 1,3-D rates. The result across zones showed that 1,3-D provided better RKN control than did aldicarb in zones with low EC_a values (high RKN risk zones exhibiting more coarse-textured sandy soils). In contrast, in low risk zones with relatively higher EC_a values (heavier textured soil), the effects of 1,3-D and aldicarb were equal and application of any of the treatments provided sufficient control. In low RKN risk zones, a farmer would often have lost money if a high rate of 1,3-D was applied. This study showed that the effect of nematicide type and rate on RKN control and cotton yield varied across management zones (MZ) with the most expensive treatment likely to provide economic benefit only in zones with coarser soil texture. This study demonstrates the value of site specific application of nematicides based on management zones, although this approach might not be economically beneficial in fields with little variability in soil texture.

Key words: 1,3-dichloropropene, aldicarb, cotton, *Gossypium hirsutum*, management zones, *Meloidogyne incognita*, root-knot nematode, precision agriculture, variable rate application.

Apparent damage from plant-parasitic nematodes, in spite of treatment, has increased across the U.S. cotton belt in the last 25 years; annual average cotton yield losses of 2.0% were reported in 1985 and 4.1% in 2010 (Blasingame and Patel, 2011). Because of its broad host range and damage potential, the Southern root-knot nematode (*Meloidogyne incognita*, RKN) is considered the most harmful nematode pest to cotton production in the U.S. In Georgia, dominant producer of Upland cotton in the U.S., estimated losses attributed to nematodes in 2010 totaled 212,500 bales with RKN responsible for 76% of those losses (Blasingame and Patel, 2011). A survey conducted in 2002 and 2003 showed that major cotton-producing counties in Georgia had RKN population densities above the recommended action threshold (100 second-stage juveniles/100 cm^3 of soil for samples collected in the fall) resulting in estimated losses of 17 million kg of cotton annually (Blasingame and Patel, 2001; Kemerait et al., 2004). Management of RKN in the southern U. S. may include crop rotation, but nematicides are the most often used control tactic (Kinloch and Rich, 1998; Wheeler et al., 1999; Zimet et al., 2002; Koenning et al., 2004). Nematicide applications are typically made at uniform rates across whole fields despite the aggregated pattern of RKN distribution (Ortiz, 2008). However, the spatial variability of nematode and damage, and the high cost of nematicides suggest a potential for site-specific applications. Variable rate application of nematicides utilizing site-specific management zones could increase cotton yield or reduce pesticide use or both. Management zones, subregions within a field each one having a similar combination of yield-limiting and reducing factors for which a single rate of a specific input is appropriate (Doerge, 1999), have been used to evaluate if nematicides (products and/or rates) have a differential response by zone with respect to nematode populations and yield. Studies in Louisiana have shown that soil texture affects the efficacy of nematicides on nematode populations and cotton yields (Erwin et al., 2007; Wolcott, 2007). When evaluating the differences in yield between 1,3-D and other treatments applied across two fields in Louisiana, coarsely textured areas in one of the fields showed a greater response to the application of 1,3-D than did areas with relatively heavier soil textures (Erwin et al., 2007). Overstreet et al. (2005) compared nematicide response across management zones and reported a 435 kg/ha yield increase only in the lighter (coarser) soil-texture zone when 1,3-D was applied.

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Wheeler et al. (1999) compared variable and single-rate applications of aldicarb on eight cotton fields in Texas and found that the variable rate treatment had greater or equal yield in only three fields; however less nematicide was applied in those three fields. In two other fields in the same experiment, the variable rate treatment used more aldicarb than did the single rate, with no difference in yield. Wrather et al. (2002) reported similar cotton yields in Missouri for uniform and variable rate aldicarb treatments, but 46% to 61% less aldicarb was used in the variable rate treatment than in the uniform rate treatment. The authors reported that spatial variation of RKN population density was associated with apparent differences in soil texture across the field, though no correlation between soil texture and nematode efficacy was presented. We hypothesized that nematode management zones, delineated from the combination of surrogate data for soil texture, can be used to support variable rate application of nematicides or for targeting soil sample collection prior to determining nematicide options.

In the Southeastern U. S., Upland cotton is grown in the Coastal Plains of Alabama, Florida, Georgia, North and South Carolina and Virginia on coarse-textured soils that often have a clay subsoil. On these soils, cotton is subject to attack by the Southern root-knot nematode (*Meloidogyne incognita,* RKN), reniform nematode (*Rotylenchulus reniformis*), Columbia Lance nematode (*Hoplolaimus columbus*), and sting nematode (*Belonolaimus longicaudatus*) among others; but the most common is the RKN. The RKN is known to be associated with sandy soils and concentrated in the sandier portions of fields. Directing treatment where the nematode is at damaging levels is a logical tactic, but sandy areas are also often the lowest-yielding because of their poor water and nutrient holding capacities, so expensive treatment of such areas might not be profitable. The objectives of this study were to determine 1) if the response of RKN population levels and cotton yield to nematicide treatments differed among management zones within a field, and 2) if the greatest economic value was provided by the same rate and type of nematicide in each RKN management zones within a field.

Materials and Methods

Study fields and experimental plan: Differences between nematicides and nematicide rates across RKN management zones were evaluated in three commercial fields (20-23 ha) located in an intensively row-cropped region of southern Georgia, USA. One of the tests was conducted at the CC field in 2007 (designated CC07). The others were conducted in 2008 and 2009 at the WHE and PRY fields (designated WHE08, WHE09, PRY08, and PRY09). The fields were planted with cotton (*Gossypium hirsutum* L.) variety Delta & Pineland (D&PL) '555 Boll-Guard, Round-Up-Ready'. Planting occurred approximately 2 weeks after each field was strip-tilled.

Management zones (MZ) for RKN were delineated based on fuzzy clustering of various surrogate data for soil texture (Ortiz et al., 2011). This approach was chosen based on the association between the level of aggregation of RKN population and soil properties, specifically differences in soil texture indirectly estimated by soil electrical conductivity (Ortiz et al., 2010); and the strong relation between nematode population and soil texture with yield (Monfort et al., 2007; Ortiz et al., 2007).

The surrogate data for soil texture used for MZ delineation included terrain elevation and slope, normalized difference vegetation index (NDVI) calculated from bare soil spectral reflectance, and apparent soil electrical conductivity (EC_a). A VERIS 3100 implement (Veris Technologies, Salina, Kansas, USA) was used to collect soil EC_a at two soil depths: 0 to 30 cm ($EC_{a\text{-shallow}}$) and 0 to 90 cm ($EC_{a\text{-deep}}$). The number of zones delineated in each field was a function of the scale of variation of terrain and edaphic features observed in a field (Ortiz et al., 2011). The zones can be used to delineate areas within a field with different levels of risk (probability) for having RKN population levels above the action threshold recommended in Georgia (Ortiz et al., 2010). Areas/zones with low populations of RKN are associated with higher mean values of EC_a, (relatively less coarse texture) and high RKN populations are associated with areas/zones with lower mean values of EC_a (relatively more coarse texture) (Ortiz, 2008; Ortiz et al., 2010). Characteristics of the RKN management zones with respect to terrain and edaphic features for the studied fields are shown in Table 1.

Nematicide treatments at each test site were arranged in a randomized complete block design. The four nematicide treatments were randomized within 16-row strips with each treatment applied to four rows. The 16-row strips were replicated several times in each field, and within the 16-row strips, 30-m sections that were randomly distributed throughout each zone were designated as blocks. The number of blocks (replications) in each zone varied from four to six depending on the size of the zone. The two nematicides evaluated were aldicarb (Temik 15G ®) and 1,3-dichloropropene (1,3-D; Telone II®) with the following treatments: aldicarb at 0.51 kg a.i./ha (T1), aldicarb at 1.0 kg a.i./ha (T2), 1,3-D at 33.1 kg a.i./ha plus aldicarb at 0.51 kg a.i./ha (T3), and 1,3-D at 66.2 kg a.i./ha plus aldicarb at 0.51 kg a.i./ha (T4). Treatment T3 is the 1,3-D rate recommended to cotton farmers to control RKN in Georgia (Kemerait, 2011). For this study, 1,3-D was applied approximately 30 cm deep during the strip-tillage operation. Between each set of 16 rows of treatments an additional strip of four rows was left as a buffer which received 0.51 kg a.i./ha aldicarb for insect control.

Data collection and analysis: Nematode population density and yield data were collected from all four rows (4 rows by 30 m) of each nematicide treated plot within each block. Composite soil samples for nematode

TABLE 1. Terrain and edaphic characteristics of the RKN management zones for the three study sites.

			Elevation (m)		ECa-shallow (mS/m)		ECa-deep (mS/m)		Soil Particle Size (Percentage)						Soil Type		
									Sand	Clay	Silt	Sand	Clay	Silt			
Field ID	County	Zone ID[a]	Mean	CV	Mean	CV	Mean	CV	Shallow (0-30cm)			Deep (0-90cm)			Symbol	Name	Description
CC 07	Colquit	1	257	1.7	1.4	115.0	1.9	74.0	89.4	1.9	8.6	88.4	2.9	8.6	Kdb	Kershaw sand	Thermic, uncoated Typic Quartzipsamments, 0 to 5% slope
		2	250	1.1	0.8	121.0	1.1	89.0	92.1	2.9	4.9	91.6	2.9	5.4			
		3	261	0.8	0.6	24.6	0.6	26.6	93.4	3.0	3.5	93.1	3.0	3.8			
WHE 08-09	Mitchell	1	105	0.7	3.0	27.5	5.4	58.0	81.3	7.6	11.1	72.0	16.0	11.4	TqB	Tift loamy sand	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults, 2 to 5% slopes
		2	108	0.6	2.6	26.5	3.1	56.0	80.5	6.7	12.7	74.6	13.0	12.5			
PRY 08-09	Colquit	1	94	0.6	1.8	39.0	3.1	47.2	86.6	2.3	11.1	84.7	3.4	11.8	TfA	Tift loamy sand	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults, 2 to 5% slopes
		2	96	0.6	1.7	40.4	2.8	50.3	87.1	2.3	10.6	86.3	3.6	10.1			

[a] Zone 3 in the CC field and zone 2 in the WHE and PRY fields were treated in this study as the zones at greatest risk for high RKN population levels.

population determination were collected from the planting row in each plot three times during 2007 and four times during the 2008 and 2009 growing seasons. Approximately 10 soil cores per plot were randomly collected from a depth of 0-20 cm using a soil probe with a 3 cm diameter opening. Second-stage juveniles (J2) were extracted from 100 cm^3 of soil by gravity sieving followed by sucrose centrifugal flotation. Cotton was harvested and the yields were determined using an Ag Leader cotton yield monitor system (Ag Leader Technology, Ames, IA) installed on a four-row picker. The system used an AgGPS 132 DGPS receiver with differential correction to continuously calculate the position of the harvester in the field.

Nematicide treatment effects and MZ differences on nematode populations over time and the interaction MZ × treatment were tested using a mixed repeated measures analysis. The same procedure was used to test within-zone differences among nematicide treatments on nematode populations over time. When testing for zone and treatment differences over time, replicate and replicate × zone were included as random effects and zone, treatment, and time as fixed effects. Within a zone, differences among nematicide treatments over time were tested with time and treatment as a fixed effect and replication as a random effect.

Nematicide treatment effects on yield and individual nematode population measurements after planting within each MZ were evaluated by mixed models analysis using the PROC MIXED procedure in SAS (v9.2, Cary, NC). Additional analysis of variance and mean comparisons were conducted using Waller Duncan K-ratio t-test ($P \leq 0.05$).

The profitability analysis was conducted using a partial budget approach to reflect differences in revenues and costs among the treatments. Revenue was based on yield and the average Southeast Base Price for November 2008 ($0.549/lb) and November 2009 ($0.519/lb). The November 2009 price included a loan deficiency payment. The resulting average base price used to calculate revenue was $0.534/lb. The nematode control costs included the nematicide treatment and application costs (fuel, labor, repairs and machinery operations). Costs based on yield included ginning, storage, and warehousing costs minus a credit for cotton seed. The average price for cotton seed during November 2008 and 2009 was $164/ton. Other costs not associated with the differences in treatments such as fertilizer, crop insurance, irrigation, etc., were assumed constant across years and treatments and therefore not included in the analysis. Adjusted revenue was calculated by subtracting the treatment and marketing costs from revenue. Adjusted revenues for the treatments were statistically analyzed by mixed models analysis using the PROC MIXED procedure of SAS and means were compared using Waller Duncan K-ratio t-test ($P \leq 0.05$). Within a zone, differences in revenue among treatments were tested using treatment as fixed effect and replication and replication × treatment as random effects.

RESULTS

Nematode Population Density:

CC field: The CC field was divided into three zones, with zone 3 having the lowest $EC_{a\text{-shallow}}$ and $EC_{a\text{-deep}}$ values and therefore being designated as the highest RKN risk zone. The repeated-measures analysis of RKN population levels throughout the season indicated differences among zones ($P = 0.093$), treatments ($P = <.0001$), and a treatment × time ($P = 0.0044$) interaction. There was not a zone × treatment interaction on nematode populations indicating that the treatments had similar effects in all zones.

Early in the season at 76 days after planting (DAP), the RKN population was low, but increased across all treatments at midseason (108 DAP) and at harvest (177 DAP), especially in zone 3 (Table 2). Regardless of treatment, the highest RKN population levels were observed in zone 3. When the repeated-measures analysis of RKN populations was conducted within a zone, treatment differences were observed only in zone 2 ($P = 0.006$) and zone 3 ($P = 0.012$) with season average RKN levels in the 1,3-D treated plots (T3 and T4) reduced 60% compared to aldicarb treated plots (T1 and T2) in both zones (Table 2). When data were analyzed by individual RKN sampling times, no significant differences in RKN populations among treatments were observed early in the season (76 DAP) in any zone. However, differences between treatments were only observed in zones 2 and 3 after midseason (108 and 177 DAP). At mid-season, 108 DAP, average RKN levels in the 1,3-D treatments (T3 and T4) were lower than the aldicarb treatments (T1 and T2) with reductions of 62%, 60%, and 72% for zone 1, 2, and 3, respectively. Populations of RKN in the 1,3-D treatments (T3 and T4) were also low compared to the aldicarb treatments at 177 DAP, and RKN levels were lowest at the high 1,3-D rate. None of the treatments differed from the standard practice by the farmer (T1) in zone 1 (Table 2).

WHE field - 2008: The WHE field had 2 zones with zone 2 having the lowest $EC_{a\text{-shallow}}$ and $EC_{a\text{-deep}}$ values and therefore being designated as the highest RKN risk zone. The repeated-measures analysis of RKN population levels throughout the season showed differences between zones ($P = 0.016$), treatments ($P = 0.0027$), and a zone × treatment interaction ($P = 0.113$) which indicated treatment differences between the zones. Overall, season average RKN levels in the 1,3-D treated plots (T3 and T4) reduced between 35% (zone 1) and 60% (zone 2) respect to the aldicarb treatment (T1 and T2) (Table 3).

When the analysis was conducted by zone, average RKN densities among treatments differed only in zone 2 ($P = 0.015$) (Table 3). Within zone 2, 1,3-D suppressed RKN more than aldicarb ($P = 0.0017$), and the high rate of 1,3-D suppressed levels more than either the low ($P = 0.019$) or high rate ($P = 0.0019$) of aldicarb. For most treatment comparisons, treatment differences were numerically greater in zone 2 than zone 1.

When RKN population data was analyzed by individual sampling time, no significant differences among treatments within either zone were observed early in the season (3 and 67 DAP) (Table 3). After mid-season, 110 DAP, significant differences between the 1,3-D treated plots and aldicarb treated plots existed in both zones with reductions of RKN levels on 1,3-D treatments with respect to aldicarb treatment quantified on 89% and 78% in zones 1 and 2, respectively. At harvest, 152 DAP, there were no significant differences in RKN population among treatments in either zone; however, RKN levels in 1,3-D treated plots were reduced 30% with respect to aldicarb treated plots in zones 2 (Table 3).

WHE field - 2009: In the repeated measures analysis, there were differences among treatments ($P = <.0001$) and a zone × treatment interaction ($P = 0.0478$) indicating that the effect of the treatments on RKN populations differed between the zones. Early in the season, 37 and 69 DAP, the RKN population was very low for all treatments in both zones. For zone 1, significant differences between the treatments were observed at 69, 125 and 183 DAP (Table 4). In contrast, no differences were observed in zone 2 except at 125 DAP ($P = 0.155$) (Table 4). At mid-season, 125 DAP, average RKN levels in the 1,3-D treatments (T3 and T4) were reduced compared to the aldicarb treatments (T1 and

TABLE 2. Seasonal *Meloidogyne incognita* (RKN) population density differences between nematicide treatments applied across the RKN management zones in the CC field.

	Edaphic -Terrain Zone Number											
	1				2				3			
	Days after planting (DAP)[a]											
	76	108	171	Average[b]	76	108	171	Average[b]	76	108	171	Average[b]
Treatment	*Meloidogyne incognita* (RKN) population density (second stage juveniles / 100 cm3 of soil)											
T1[c] - aldicarb (0.51 kg a.i./ha)	0.70a	154.4a	78.3a	77.8a	20.7a	218.3ab	69.3b	102.8a	40.7a	323.0a	157.3a	173.7ab
T2 - aldicarb (1.0 kg a.i./ha)	24.0a	132.0a	148.0a	101.3a	10.7a	324.0a	123.7a	152.8a	38.0a	360.3ab	188.0a	195.4a
T3[d] - 1,3-D(33.1 kg a.i./ha) + aldicarb (0.51 kg a.i./ha)	4.70a	151.2a	34.0a	63.3a	9.0a	97.0ab	66.0b	57.3a	24.0a	135.3ab	111.7a	90.3ab
T4 - 1,3-D (66.2 kg a.i./ha) + aldicarb (0.51 kg a.i./ha)	12.7a	61.6a	54.7a	43.0a	18.0a	85.3b	30.7b	44.7a	14.0a	68.7a	89.3a	57.3b
Pr > |*t*|	*0.5609*	*0.5924*	*0.2473*	*0.2443*	*0.8305*	*0.0180*	*0.0090*	*0.006*	*0.489*	*0.0235*	*0.2346*	*0.0126*

[a] Means within columns followed by the same letter are not significantly different ($P \leq 0.05$) according to Waller-Duncan K-ratio t-test.
[b] Season average of nematode population within a management zone. Treatment comparisons were conducted by repeated-measures using RKN population measured at various DAP.
[c] aldicarb at a formulation of 0.51 kg a.i./ha and 1.0 kg a.i./ha correspond to rate of 3.4 kg/ha and 6.7 kg/ha, respectively.
[d] 1,3-D at a formulation of 33.1 kg a.i./ha and 66.2 kg a.i./ha correspond to rate of 28 liters/ha and 56 liters/ha, respectively.

TABLE 3. Seasonal *Meloidogyne incognita* (RKN) population differences between nematicide treatments applied across the RKN management zones in the WHE08 field.

	Edaphic -Terrain Zone Number									
	1					2				
	Days after planting (DAP)[a]									
	3	67	110	152	Average[b]	3	67	110	152	Average[b]
Treatment	*Meloidogyne incognita* (RKN) population density (second stage juveniles / 100 cm3 of soil)									
T1[c] - aldicarb (0.51 kg a.i./ha)	3.2a	120.0a	217.2a	271.2a	152.9a	14.0a	10.6a	180.8a	122.4a	82.0ab
T2 - aldicarb (1.0 kg a.i./ha)	2.8a	49.0ab	143.2ab	142.0a	84.2a	24.8a	20.4a	222.0a	154.2a	105.3a
T3[d] - 1,3-D(33.1 kg a.i./ha) + aldicarb (0.51 kg a.i./ha)	2.0a	1.2b	29.4b	313.4a	86.5a	16.0a	0.6a	47.2b	127.2a	47.7bc
T4 - 1,3-D (66.2 kg a.i./ha) + aldicarb (0.51 kg a.i./ha)	0.2a	2.4b	8.0b	271.0a	70.4a	0.0a	0.2a	40.0b	66.8a	26.7c
$Pr > \|t\|$	*0.501*	*0.072*	*0.013*	*0.493*	*0.300*	*0.384*	*0.119*	*0.002*	*0.313*	*0.015*

[a] Means within columns followed by the same letter are not significantly different ($P \leq 0.05$) according to Waller-Duncan K-ratio t-test.
[b] Season average of nematode population within a management zone. Treatment comparisons were conducted by repeated-measures using RKN population measured at various DAP.
[c] aldicarb at a formulation of 0.51 kg a.i./ha and 1.0 kg a.i./ha correspond to rate of 3.4 kg/ha and 6.7 kg/ha, respectively.
[d] 1,3-D at a formulation of 33.1 kg a.i./ha and 66.2 kg a.i./ha correspond to rate of 28 liters/ha and 56 liters/ha, respectively.

T2) with reductions of 66% in zone 1 and 73% in zone 2. At harvest, 183 DAP, the RKN population in the 1,3-D treatments (T3 and T4) was reduced 59% compared to the aldicarb treatments (T1 and T2) in zone 1 and 25% in zone 2.

PRY field - 2008: The PRY field had 2 zones with zone 2 having the lowest $EC_{a\text{-shallow}}$ and $EC_{a\text{-deep}}$ values, and therefore being designated as the highest RKN risk zone. The repeated-measures analysis of RKN population levels throughout the season indicated that the treatments had similar effects in all zones (there was not a zone x treatment interaction). Within a zone, average RKN population differences among treatments were observed for zone 1 ($P = 0.009$) and zone 2 ($P = 0.002$) (Table 5). Overall, season average RKN levels in the 1,3-D treated plots (T3 and T4) reduced between 59% (zone 1) and 91% (zone 2) with respect to the aldicarb treatment (T1 and T2) (Table5). As observed in the other two fields, the RKN population early in the season, 24 and 72 DAP, was low for all treatments in both zones. After mid-season, 116 DAP, significant differences in RKN population levels among the treatments were observed in both zones. On average, the RKN population levels in 1,3-D treated plots compared to aldicarb treated plots was reduced 75% in zone 1 and 95% in zone 2. There were no significant differences between rates either for aldicarb or 1,3-D in either zone. At harvest, 177 DAP, there were no significant differences in RKN population among treatments in either zone. However, the RKN population in the 1,3-D treatments (T3 and T4) was reduced 80% compared to the aldicarb treatments (T1 and T2) in zone 2.

PRY field - 2009: The repeated-measures analysis of RKN population levels throughout the season did not showed differences between zones or treatment × zone interaction, only treatment differences ($P = 0.004$) were observed. When the analysis was conducted by zone, treatment differences were only observed in zone 1 ($P = 0.068$) (Table 6). Overall, RKN population levels in both zones were lower in 1,3-D treated plots than in

TABLE 4. Seasonal *Meloidogyne incognita* (RKN) population differences between nematicide treatments applied across the RKN management zones in the WHE09 field.

	Edaphic -Terrain Zone Number									
	1					2				
	Days after planting (DAP)[a]									
	37	69	125	183	Average[b]	37	69	125	183	Average[b]
Treatment	*Meloidogyne incognita* (RKN) population density (second stage juveniles / 100 cm3 of soil)									
T1[c] - aldicarb (0.51 kg a.i./ha)	0.0a	96.0a	912.3a	722.7a	432.7a	0.0a	19.3a	676.0a	407.3a	275.7ab
T2 - aldicarb (1.0 kg a.i./ha)	2.7a	55.0ab	532.6ab	394.7ab	246.2b	0.0a	8.0a	996.7a	572.0a	394.2a
T3[d] - 1,3-D(33.1 kg a.i./ha) + aldicarb (0.51 kg a.i./ha)	0.0a	0.0b	220.7b	230.0b	112.7b	0.0a	16.0a	367.3a	427.3a	202.7ab
T4 - 1,3-D (66.2 kg a.i./ha) + aldicarb (0.51 kg a.i./ha)	2.7a	2.0b	275.0b	231.3b	127.7b	0.0a	10.0a	92.0b	302.7a	101.2b
$Pr > \|t\|$	*0.476*	*0.074*	*0.014*	*0.025*	*0.0032*	-	*0.653*	*0.155*	*0.442*	*0.245*

[a] Means within columns followed by the same letter are not significantly different ($P \leq 0.05$) according to Waller-Duncan K-ratio t-test.
[b] Season average of nematode population within a management zone. Treatment comparisons were conducted by repeated-measures using RKN population measured at various DAP.
[c] aldicarb at a formulation of 0.51 kg a.i./ha and 1.0 kg a.i./ha correspond to rate of 3.4 kg/ha and 6.7 kg/ha, respectively.
[d] 1,3-D at a formulation of 33.1 kg a.i./ha and 66.2 kg a.i./ha correspond to rate of 28 liters/ha and 56 liters/ha, respectively.

TABLE 5. Seasonal *Meloidogyne incognita* (RKN) population density differences between nematicide treatments applied across the RKN management zones in the PRY08 field.

	Edaphic -Terrain Zone Number									
	1					2				
	Days after planting (DAP)[a]									
	24	72	116	177	Average[b]	24	72	116	177	Average[b]
Treatment	*Meloidogyne incognita* (RKN) population density (second stage juveniles / 100 cm3 of soil)									
T1[c] - aldicarb (0.51 kg a.i/ha)	1.2a	50.0a	402.8a	185.6a	159.9a	0.8a	21.8a	744.4a	253.2a	255.1a
T2 - aldicarb (1.0 kg a.i/ha)	2.4a	26.4b	570.0a	142.2a	185.3a	1.6a	23.6a	486.8a	198.0a	177.5a
T3[d] - 1,3-D(33.1 kg a.i./ha) + aldicarb (0.51 kg a.i./ha)	0.8a	4.0c	186.2b	129.4a	80.1b	0.0a	0.6a	25.2b	44.8a	17.7b
T4 - 1,3-D (66.2 kg a.i./ha) + aldicarb (0.51 kg a.i./ha)	0.0a	5.8cb	28.0b	206.4a	60.1b	0.4a	0.2a	41.2b	42.2a	21.0b
Pr > |*t*|	*0.304*	*0.002*	*0.001*	*0.808*	*0.009*	*0.652*	*0.116*	*0.001*	*0.184*	*0.001*

[a] Means within columns followed by the same letter are not significantly different ($P \leq 0.05$) according to Waller-Duncan K-ratio t-test.
[b] Season average of nematode population within a management zone. Treatment comparisons were conducted by repeated-measures using RKN population measured at various DAP.
[c] aldicarb at a formulation of 0.51 kg a.i./ha and 1.0 kg a.i./ha correspond to rate of 3.4 kg/ha and 6.7 kg/ha, respectively.
[d] 1,3-D at a formulation of 33.1 kg a.i./ha and 66.2 kg a.i./ha correspond to rate of 28 liters/ha and 56 liters/ha, respectively.

aldicarb treated plots. At 39 and 67 DAP, the RKN population was very low and did not differ among treatments in either zone. Treatment differences were only observed at mid-season (123 DAP) for both zones. At 123 DAP, the RKN levels in the 1,3-D plots (T3 and T4) were reduced compared to the aldicarb treated plots (T1 and T2) by 85% in zone 1 and 62% in zone 2.

Yield and Profitablity

CC field: Yield differences among the zones were observed regardless of the nematicide treatment (P = 0.0006). Average yields of 994 kg/ha, 709 kg/ha, and 417 kg/ha were observed for zones 1, 2 and 3, respectively. Nematicide treatments did not affect yields the same in each zone (a zone × treatment interaction, $P < 0.0001$) (Table 7). Yields were greater in the 1,3-D (T3 and T4) compared to the aldicarb treatments (T1 and T2). Yield increases on 1,3-D treated plots were 12%, 28% and 70% for zones 1, 2, and 3, respectively. Revenue differences among treatments were very small in the three zones, and differences (P = <. 0001) were only observed in zone 3 with 1,3-D treated plots being more profitable than aldicard treated plots (Table 8).

WHE field: In 2008, yield differences between the zones were observed regardless of the nematicide treatment (P = 0.015), and zone influenced the treatment effects (zone × treatment interaction, P = 0.053). Average yields of 1046 kg/ha and 952 kg/ha were observed for zones 1 and 2, respectively. Yield differences among the nematicide treatments were only observed in zone 2 (P = 0.058) (Table 7). Yield from the highest rate of 1,3-D (T4) was higher than the other treatments in zone 2. The lint yield in 2009 was higher than 2008 regardless of the treatment. Yield differences among the treatments were observed in zone 2 (P = 0.036), but unlike other fields/zones yield reductions on the 1,3-D treated plots (T3 and T4) were observed respect to aldicarb treated plots (T1 and T2). Revenue did not differ among nematicide treatments in either zone during 2008 (Table 8). In 2009, however, differences in revenue

TABLE 6. Seasonal *Meloidogyne incognita* (RKN) population density differences between nematicide treatments applied across the RKN management zones in the PRY09 field.

	Edaphic -Terrain Zone Number									
	1					2				
	Days after planting (DAP)[a]									
	39	67	123	166	Average[b]	39	67	123	166	Average[b]
Treatment	*Meloidogyne incognita* (RKN) population density (second stage juveniles / 100 cm3 of soil)									
T1[c] - aldicarb (0.51 kg a.i./ha)	18.7a	20.0a	420.7a	347.3a	201.7a	0.7a	14.0a	361.3a	397.3a	193.3a
T2 - aldicarb (1.0 kg a.i./ha)	6.3a	49.0a	388.3a	333.3a	194.2ab	0.7a	16.0a	168.7cb	318.6a	126.0ab
T3[d] - 1,3-D(33.1 kg a.i./ha) + aldicarb (0.51 kg a.i./ha)	0.0a	30.0a	89.0b	247.3a	90.6ab	0.0a	0.7a	190.0b	208.0a	99.7ab
T4 - 1,3-D (66.2 kg a.i./ha) + aldicarb (0.51 kg a.i./ha)	1.3a	29.3a	33.7b	120.7a	46.2b	0.3a	1.7a	11.0c	126.3a	34.8b
Pr > |*t*|	*0.378*	*0.749*	*0.027*	*0.622*	*0.067*	*0.752*	*0.287*	*0.010*	*0.594*	*0.2016*

[a] Means within columns followed by the same letter are not significantly different ($P \leq 0.05$) according to Waller-Duncan K-ratio t-test.
[b] Season average of nematode population within a management zone. Treatment comparisons were conducted by repeated-measures using RKN population measured at various DAP.
[c] aldicarb at a formulation of 0.51 kg a.i./ha and 1.0 kg a.i./ha correspond to rate of 3.4 kg/ha and 6.7 kg/ha, respectively.
[d] 1,3-D at a formulation of 33.1 kg a.i./ha and 66.2 kg a.i./ha correspond to rate of 28 liters/ha and 56 liters/ha, respectively.

TABLE 7. Influence of nematicide treatments on cotton yield within the RKN management zones.

	Field ID										
	CC07[a]			WHE08		WHE09		PRY08		PRY09	
	Zone ID										
	1	2	3	1	2	1	2	1	2	1	2
Treatments[b]	Lint (kg/ha)[c]										
T1[d]	962.9a	634.7a	273.5a	971.1a	957.2ab	1239.4a	1268.1a	478.6a	670.2a	907.6a	896.8a
T2	862.2a	612.9a	327.9a	1042.5a	946.8ab	1202.8a	1262.7a	587.0a	695.5a	916.8a	851.2a
T3[e]	991.8a	753.0b	509.7b	1103.4a	836.31b	1181.4a	1163.7b	542.3a	696.8a	1037a	973.8a
T4	1087.0a	833.3b	553.1b	1067.7a	1069.2a	1140.5a	1131.1b	626.4a	748.8a	948.2a	1032.0a
$Pr > \|t\|$	*0.1260*	*0.0021*	*<.0001*	*0.3796*	*0.058*	*0.3355*	*0.036*	*0.741*	*0.907*	*0.245*	*0.080*

[a] CC07 = CC field in 2007, WHE08 = WHE field in 2008, WHE09 = WHE field in 2009, PRY08 = PRY field in 2008, PRY09 = PRY field in 2009.
[b] T1: aldicarb 0.51 kg a.i./ha, T2: aldicarb 1.0 kg a.i./ha, T3: 1,3-D 33.1 kg a.i./ha + aldicarb 0.51 kg a.i./ha, T4: 1,3-D 66.2 kg a.i./ha + aldicarb 0.51 kg a.i./ha.
[c] Means within columns followed by the same letter are not significantly different (P<=0.05) according to Waller-Duncan K-ratio t-test.
[d] aldicarb at a formulation of 0.51 kg a.i./ha and 1.0 kg a.i./ha correspond to rate of 3.4 kg/ha and 6.7 kg/ha, respectively.
[e] 1,3-D at a formulation of 33.1 kg a.i./ha and 66.2 kg a.i./ha correspond to rate of 28 liters/ha and 56 liters/ha, respectively.

were observed among the treatments in zones 1 (P = 0.003) and 2 (P = <.0001) with the 1,3-D treatments having the lowest revenue compared the aldicarb treatments (Table 8).

PRY field: In 2008, yield differences between the zones were observed regardless of the nematicide treatment (P = 0.097), however the zone × treatment interaction was not significant. Yield increments on 1,3-D treated plots respect to aldicarb plots were 9% and 6% for zones 1 and 2, respectively. In both zones, yield was slightly higher from plots that received 1,3-D at 66.2 kg a.i./ha (T4) rate. In 2009, average yields increased considerably compared to 2008 (Table 7) but no differences between the zones or zone × treatment interaction was observed. In 2009, yield among the treatments was only different in zone 2 (P = 0.080), but yield increases in the 1,3-D treated plots (T3 and T4) compared to aldicarb treated plots (T1 and T2) corresponded to 8% in zone 1 and 13% in zone 2. Revenue differences were not observed among the treatments in zones 1 or 2 in 2008 or in 2009.

DISCUSSION

The aggregated spatial distribution of RKN suggests that site-specific application of nematicides may be an effective strategy to control this nematode and reduce yield losses, and also reduce the amount of nematicides used. Data collected from 11 cotton fields showed that the identification of areas at risk for high RKN populations within cotton fields is possible using $EC_{a\text{-shallow}}$ and $EC_{a\text{-deep}}$ data (Ortiz et al., 2011). A negative spatial correlation between RKN population and $EC_{a\text{-deep}}$ has been shown, which indicates that high levels of RKN are associated with sandy soil areas (Khalilian et al., 2001; Monfort et al., 2007; Ortiz et al., 2010; Ortiz et al., 2011). According to Ortiz et al. (2011), soil texture data, in the form possibly of soil EC_a data, may be used to delineate management zones that can be sampled independently to assess the actual nematode levels. They found that areas within a field with the lowest soil EC_a values have a higher likelihood of having high RKN populations and therefore, those areas would be likely to benefit from a nematicide application.

In the present study and independent of the treatment, average RKN population variations among management zones were only observed in the fields with largest edaphic-terrain zone differences (CC and WHE fields) (Table 1), therefore higher RKN population response to the nematicide treatments between the zones were observed in those fields. At those fields it was observed that nematicide treatments, especially 1-3D, had a much higher nematode population reduction in zones

TABLE 8. Average revenue by zone and treatment.

		Revenue (US$/ha)[a]				
		Nematicide treatment[cd]				
Field[b]	Zone	T1[e]	T2	T3[f]	T4	$Pr > \|t\|$
CC07	1	554a	486a	541a	562a	*0.427*
	2	361a	340a	402a	413a	*0.701*
	3	151a	174a	260b	250b	*<.0001*
WHE08	1	592a	627a	627a	563a	*0.339*
	2	584a	568ab	462b	564ab	*0.060*
WHE09	1	758a	713ab	689b	608c	*0.003*
	2	773a	767a	665b	602b	*<.0001*
PRY08	1	406a	412a	375a	366a	*0.893*
	2	287a	345a	280a	290a	*0.927*
PRY09	1	546a	509a	547a	541a	*0.821*
	2	553a	549a	586a	489a	*0.154*

[a] Revenue adjusted for marketing and treatment costs.
[b] CC07 = CC field in 2007, WHE08 = WHE field in 2008, WHE09 = WHE field in 2009, PRY08 = PRY field in 2008, PRY09 = PRY field in 2009.
[c] T1: aldicarb 0.51 kg a.i./ha; T2: aldicarb 1.0 kg a.i./ha; T3: 1,3-D 33.1 kg a.i./ha + aldicarb 0.51 kg a.i./ha, T4; 1,3-D 66.2 kg a.i./ha + aldicarb 0.51 kg a.i./ha.
[d] Means within columns followed by the same letter are not significantly different (P≤0.05) according to Waller-Duncan K- ratio t-test.
[e] aldicarb at a formulation of 0.51 kg a.i./ha and 1.0 kg a.i./ha correspond to rate of 3.4 kg/ha and 6.7 kg/ha, respectively.
[f] 1,3-D at a formulation of 33.1 kg a.i./ha and 66.2 kg a.i./ha correspond to rate of 28 liters/ha and 56 liters/ha, respectively.

with the lowest mean values of $EC_{a\text{-shallow}}$ and $EC_{a\text{-deep}}$ and therefore the coarsest soil texture (zone 3 in the CC field and zone 2 in the WHE). Fields having the smallest zone differentiation respect to edaphic-terrain properties (PRY) did not exhibited RKN population differences between zones. For the PRY field, nematode population response to nematicide treatments were observed in both zones, especially at mid-season (166 DAP); however, the nematicide responses were similar in both zones (PRY09, Table 6).

Overall, the nematicide treatments response among zones was more evident at mid-season (108 through 125 DAP), with 1,3-D treated plots exhibiting higher reduction in RKN population in the highest RKN risk zones (zone 3 in the CC field, and zone 2 in the WHE and PRY fields) compared to the low RKN risk zone (zone 1 in the CC, WHE, and PRY fields). In those zones, the highest rate of 1,3-D provided the greatest RKN population control, and the reduction was still evident until harvest in most of the cases.

The zone differences and zone by treatment interaction on RKN population and the subsequent impact on yield was very well illustrated in the CC field, the field with the largest zone differences on edaphic-terrain properties. The differences in RKN levels between treatments by zone, especially the control of nematodes by 1,3-D with respect to aldicarb observed in zones 2 and 3 resulted in yield increases of 21% and 43%, respectively. For those zones, the high rate of 1,3-D (66.2 kg a.i./ha – T4) provided the highest nematode control which resulted in the largest yield increase. In contrast, the low response of nematode population to the different nematicide treatments observed in zone 1 resulted on very small yield changes. These results were consistent with Overstreet and Wolcott (2007) in Louisiana, who reported from an evaluation of nematode management zones in cotton fields that yield response to zone application of 1,3-D was observed in one zone of a six zones field and two zones from another field with seven zones. In a similar study Overstreet et al. (2007) found from seven fields studied in Louisiana that zone application of 1,3-D resulted in zone responses from 17% to 100%.

A case of low or no response to zone application of nematicide was observed at the PRY field, the field with the smallest zone differences in edaphic-terrain properties. At this field, there were neither nematode differences between zones nor interaction zone x treatment (PRY09); therefore, no yield benefit from zone application of nematicides was observed. The results from this study at the CC and WHE fields exemplify why significant differences in management zones must exist for the zone application of nematicide to produce the expected differential nematode control and yield benefits.

The presence of high RKN population levels in soil with low water availability, such as coarse-textured sandy areas with the lowest $EC_{a\text{-deep}}$ values, may exacerbate yield losses (Wheeler et al, 1991). Ortiz et al. (2007) evaluated the relationship between cotton yield, soil physical and chemical properties, and RKN population in two cotton fields and found that the presence of high RKN populations on coarse textured areas exacerbated yield losses due to the low uptake of water and potassium by RKN infected plants and the concomitant low availability of these resources in sandy areas. In the CC field, the yield average across treatments for zone 3, the high RKN risk zone with the lowest $EC_{a\text{-deep}}$ values, was 489 kg/ha of cotton lint, but the average yield in 1,3-D treated plots in that zone was 647 kg/ha, a 25% increase. In the high RKN risk zones of the WHE08 and PRY08 fields, yield increases in areas treated with the high rate of 1,3-D relative to the zone average were 12% and 6%, respectively. The application of 1,3-D on high RKN risk zones resulted in yield increases in all three fields, but the amount of increase was field specific. These experiments strongly suggest that the differences are related to between-zone differences in soil properties and topography, and the interaction of soil properties and rainfall at the locations.

Rainfall is an important factor that influences the effect that RKN populations and nematicide treatment have on yield. In 2009 at the WHE and PRY fields, there were no significant yield differences among the treatments in either management zone. The high yield observed in 2009 compared to 2008 and the small differences between nematicides and rates could be explained by the high number of rainy days that occurred during the 2009 cotton growing season: there were 6 rainy days in May, 2 in July, 6 in August, 6 in September, and 10 in October. This frequency of rain could reduce the effect of the plant water stress that nematode parasitism might cause.

The economic analysis showed that the site-specific application of nematicides is cost effective where significant within-field variability exists in factors that influence RKN population spatial distribution like soil textural properties (Table 1). The CC field exhibited significant soil and terrain variability which resulted in distinct management zones with different levels of RKN population density. In the low RKN risk zone of this field, the low RKN populations and small yield differences between the 1,3-D and aldicarb treatments explained the lack of profitability of the 1,3-D application compared to aldicarb. Contrasting results in the high RKN risk zone of this field (zone 3) showed that the application of 1,3-D at any rate improved RKN control and yield compared to aldicarb treatments resulting in a positive economic return. Different from the benefits of zone application of nematicides observed on the CC field was the lack of benefits observed at the PRY field, the smallest within-field variability. The management zones delineated for the PRY exhibited very similar soil and terrain properties; therefore, the absence of differences in RKN population between the zones which resulted in none economic benefit from using 1,3-D rather than aldicarb. Furthermore, in the low RKN risk zone (PRY09), the small yield increase in plots treated with the high rate of 1,3-D was insufficient to cover its application cost, resulting in economic losses. Research studies conducted on Mississippi Delta soils in Louisiana indicated that a yield increase of 90-112 kg/ha was necessary to cover the cost of 1,3-D application at the rate of 28 Liter/ha (Erwin et al., 2007). In 2009, excessive rainfall reduced the benefit of 1,3-D application on nematode control and yield increase, resulting in economic losses for the WHE and PRY field, especially at the high rate of 1,3-D (66.2 kg a.i./ha). Kinloch and Rich (1998) reported a similar effect of rainfall on nematicide efficacy. The results of on-farm trials conducted in Florida (Santa Rosa County) in 1995 showed that excessive rainfall (98 cm) from August to near cotton harvest ameliorated the potential detrimental effects caused by nematodes and reduced the value that could have been gained by the application of various 1,3-D treatments. For risk-tolerant producers, climate forecasts for the cotton growing season could influence the choice of nematicide.

This study supports the site-specific application of nematicides (product and rate) as a management strategy to reduce yield losses associated with damaging RKN population levels. RKN population and yield data frequently showed a differential treatment response by zone (treatment × zone interaction) suggesting that 1,3-D be applied only to the high RKN risk zone, and that conclusion was supported in some years by the economic analysis. The best response to zone application of nematicide is seen when large between-zone differences exist in soil textural properties, but the site specific application of nematicides may not be economically beneficial in fields with low variability. In fields where significant variability does exist, nematode management zones based on soil EC_a are an effective way to target nematode sampling that can be used to determine where nematicides are likely to be economically beneficial and which nematicide and rate are likely to provide the greatest benefits.

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