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The Relationship Between Environmental Variables and Response of Cotton to Nematicides

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Abstract: Nematicide/irrigation rate trials were conducted in Texas (TX) in 2009 and 2010 in cotton grown at three irrigation rates, where irrigation rate (base (B), B - 33%, B + 33%) was the main plot and treatment (untreated check, aldicarb, and nematicide seed treatment (NST) and NST + aldicarb) were the subplots. Aldicarb improved cotton lint yield with the base (medium) irrigation rate over the untreated check, but not at the B - 33% and B + 33% irrigation rates. In a second evaluation, 20 tests conducted over 7 yr at the same field in TX and 12 tests conducted over 6 yr at the same field in Alabama (AL) were examined for impact of environmental variables (EV) on the response to NST (containing thiodicarb or abamectin), aldicarb, a nontreated check (CK), insecticide seed treatment (TX only), and a combination of NST + aldicarb + oxamyl (NST/A/O, AL only) on root galls (TX only), early season nematode eggs (AL only), and yield (both sites). Galls/root system were lower with aldicarb-treated plots, than for the CK- or NST-treated plots. As water (irrigation plus rain) in May increased, galls/root system increased for CK or insecticide-only-treated plots, and decreased for NST- and aldicarb-treated plots, suggesting efficacy of nematicides was strongly improved by adequate soil moisture. Nematode reproduction was not affected by EV in either location, though yield was negatively affected by root-knot nematode eggs in AL at 60 d. Yield in both AL and TX was negatively related to temperature parameters and positively related to water parameters. With the addition of EV in TX, chemical treatments went from not significantly different in the absence of EV to aldicarb-treated plots having higher yields than nonnematicide-treated plots in the presence of EV. In AL, NST/A/O-treated plots yielded similar to aldicarb and better than CK or NST in the absence of EV and had significantly higher yields than all other treatments in the presence of most EV.

Key words: abamectin, aldicarb, *Gossypium hirsutum*, *Meloidogyne incognita*, oxamyl, thiodicarb.

Effective thrips management and partial control of nematodes with aldicarb (Temik 15G, Bayer CropScience, Research Triangle Park, NC) has been achieved in cotton production for many decades. In recent years, nematicide seed treatments (NST) were commercialized with much lower health risks compared to aldicarb. Aldicarb rapidly oxidizes to aldicarb sulfoxide, which is mobile in water. The movement of any chemical in soil is affected by physical properties of that chemical (Q-value, which is related to polarity), and the adsorption characteristics of the soil and water flux (Bromilow, 1973; Angier et al., 2005). The application method for a chemical also affects its initial distribution, but then rainfall or irrigation and plant water uptake will redistribute the chemical. For aldicarb, most of the nematode control occurs in the soil rather than inside the plant (Steele and Hodges, 1975). In a silt loam soil, aldicarb and its derivatives were found to redistribute upward toward the bed surface and also toward the sides of the bed over time and with the application of water (Hough et al., 1975). Significant loss of aldicarb presumably because of leaching, only occurred with rainfall of 3 cm or more at one time (Andrawes et al., 1971). Mobility and ability of second-stage juveniles (J2) of *Heterodera schachtii* to infect roots were substantially affected at concentrations of 1 µg/ml of aldicarb or aldicarb sulfoxide (Hough and Thomason, 1975).

The NST thiodicarb (Aeris™, Bayer CropSciences, Research Triangle Park, NC) and abamectin (Avicta® Complete Cotton, Syngenta, Greensboro, NC) are labeled for nematicide use in the United States. There is little information available on distribution of thiodicarb or abamectin in soil when applied as a seed treatment.

Abamectin (B1a) is virtually insoluble in water and is quickly adsorbed to soil organic matter (Bull et al., 1984). Nematode paralysis caused by aldicarb can be reversed if J2 are removed from effective concentrations; however, abamectin is highly toxic to *M. incognita* J2 (LD50 of 1.56 µg/ml) and the damage is irreversible (Fraske and Starr, 2006). Abamectin-treated seed can reduce gall formation by *M. incognita*, though only a small portion of the chemical was transferred to the developing root system in greenhouse pot studies (Fraske and Starr, 2007). Field results with abamectin (Avicta® 500 FS, Syngenta, Greensboro, NC) have been variable (Lawrence and Lawrence, 2007; Erwin et al., 2008; Kemerait et al., 2008).

Thiodicarb has historically been used as an insecticide (Larvin®, Bayer CropSciences, Research Triangle Park, NC). There is little published information on the properties of this chemical when applied as a nematicide seed treatment. Thiodicarb has very poor mobility in water and degrades rapidly (half life of < 4 hr) to methomyl when applied to soil surfaces (Jones et al., 1989). Methomyl is more mobile in soil and has a half life of 0.5 to 1.6 mon in subsoils (Jones et al., 1989). Results with thiodicarb as a NST have also been variable (Lawrence and Lawrence, 2007; Erwin et al., 2008; Kemerait et al., 2008).

Oxamyl (Vydate® CLV, Dupont, Wilmington, DE) is an insecticide/nematicide that has the unusual property of being mobile both upward and downward in plants (Harvey et al., 1978). The concentration of oxamyl

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in roots from a foliar application is only a fraction (0.1%) of what is found in the above ground plant parts (Harvey and Han, 1978). Nematode control is achieved predominantly through downward movement of the product. Oxamyl applied on the foliage inhibited *Rotylenchulus reniformis* penetration into cotton roots, when multiple applications were made at 5-d intervals (Rich and Bird, 1973). Oxamyl degrades rapidly in soil (half life is 1 wk or less in soil, Harvey and Han, 1978).

The impact of water flux on movement and distribution of aldicarb in soil is well documented, but similar data are lacking for NST. The objectives of this study are to (i) determine if the effect of aldicarb or NST on cotton yield is similar across different irrigation rates; (ii) determine if early season environmental conditions (water and temperature) influence the ability of NST and aldicarb to control nematodes in field soils; and (iii) whether environmental conditions influence the efficacy of NST and aldicarb on cotton yield in field trials.

The approach to determine the second and third objectives was to use environmental measurements taken from test sites where numerous small- or large-plot, replicated tests were conducted over a number of years. A mixed linear model analysis provides the technique to look at both fixed treatment effects (nematicides or untreated checks), random effects unique to the experiments (replication, trial, and interaction between these random and fixed effects), and the use of a covariate analysis to account for specific environmental effects on the measurements of interest (yield, root galling, nematode population density). It combines both the benefit of an analysis of variance (ANOVA) approach with the test structure used to reduce overall variance, and regression analysis with quantitative variables. A mixed linear models approach with a covariate factor (linear or interaction with treatment) is designed to adjust the y-intercept (i.e., which represents the simple means) to the center of the covariate value, which is where the variance is lowest.

The goal of this project is to determine the effects of water and temperature on nematicide performance and subsequent influence on yield, in a real-world setting with all the "noise" that comes from field applications and weather variations. It is particularly important with respect to the usefulness of seed treatments, which have a much shorter history of use than aldicarb.

Materials and Methods

Nematicide/Irrigation rate experiments in TX: In 2009 and 2010, a large-plot experiment was conducted with three irrigation rates (whole plots) and four chemical treatments (subplots) with three replications (REP) for irrigation rate. The chemical treatments were an untreated check; aldicarb at 0.59 and 0.84 kg ai/ha (in-furrow, at-planting); and thiodicarb (0.375 mg ai/seed) + imidacloprid (insecticide, 0.375 mg ai/seed) seed treatment (Aeris) plus aldicarb at 0.84 kg ai/ha (at-plant, below the seed). In 2010 only, Aeris alone was also included as a treatment. The cotton cultivar was Fibermax 9160B2F (B2 = Bollgard II and F = Roundup Ready Flex (Bayer CropScience, Lubbock, TX)). The plots were planted in a circle with a 60° arc, with the smallest plot containing 0.034 ha and the largest plot containing 0.093 ha. Plots were planted on 7 May 2009 and 12 May 2010. Plots were irrigated uniformly to establish stands, and irrigation rate treatments were initiated on 5 August 2009 and 24 June 2010. Total irrigation for crop establishment prior to initiating irrigation rates were 6.4 and 4.6 cm in 2009 and 2010, respectively. Once irrigation rates (base (B) and B + 33% and B - 33%) were initiated, they continued for the rest of the growing season. Unless heavy rainfall occurred or crop water demand was greatly reduced, the plots were irrigated with the prescribed rates every 3.5 d with 1.02 cm in 2009 and 1.17 cm in 2010 for the base irrigation rate. These rates were considered sufficient to obtain good yields or were the maximum amount of irrigation that could be pumped from the wells to cover the 48 ha under the center pivot system.

On 9 June 2009, 40 plants from each plot were dug and the galls per root were counted. On 24 June 2010, 20 plants from each plot were dug and galls were counted. In each case, plants were selected for removal by taking a certain number of paces, so that the entire plot length was sampled. Since the plot lengths varied due to being an arc of a circle, the number of paces between sampling points increased as plot length increased. Composite soil samples consisting of 20 sampling points per plot were taken on 20 July 2009 and 17 August 2010. At each sampling spot, a narrow bladed shovel was used to a depth of 20 cm near the taproot, and soil and roots were removed (approximately 50 cm^3) from the bottom 5 to 7 cm. A pie-pan assay (Thistlethwayte, 1970) was used to extract J2 of *M. incognita* from 200-cm^3 soil + roots. Eggs of *M. incognita* were extracted by adding 500 cm^3-soil + roots to 2 liter of water, stirring vigorously, then letting the soil settle out for 15 sec., and pouring the water plus organic matter through a sieve with a pore size of 191 μm. The organic matter was washed into a beaker and stirred in a 10% solution of bleach (0.06% NaOCl) for 5 min. The eggs were then caught on a sieve with a 25-μm pore size, which was placed under a sieve with a 191-μm pore size to catch the larger organic matter. The eggs were then stained (Byrd et al., 1983). Midseason root-knot density (Pm) per plot was calculated as the number of eggs or J2/ 500-cm^3 soil, whichever value was higher. Usually eggs have a much higher density at midseason than do J2, so typically Pm is the same as the egg density. However, extraction of both stages was always conducted.

Plots were harvested with a four-row cotton stripper on 23 October 2009 and 25 October 2010. The harvested cotton from each plot was placed in a weigh wagon equipped with load cells to obtain the whole plot weight. A 1,000-g subsample was taken from the harvested cotton in each plot and ginned to determine the percentage of the harvested cotton that was lint. Stripper harvested cotton contains lint, seed, burrs, bracts, and some branches, while picker cotton (see AL data) contains just lint and seed and yield is presented as a combined weight of lint and seed. The plot weight was multiplied by the percentage of lint to obtain yield, and then adjusted for plot size to kg of lint/ha.

The number of galls/plant was averaged for each plot. Number of galls, $\log_{10}(Pm + 1)$ and yield (kg lint/ha) were analyzed using Proc Mixed in SAS, version 9.1 (SAS Institute, Cary, NC). The model statement for galls had only chemical treatment (CHEM) since the measurement was made before irrigation treatments (rates) were applied. The random statement contained year, REP (year) and year × CHEM. The Satterthwaite option (Satterthwaite, 1946) was used in all analyses to adjust denominator degrees of freedom to match adjustments in the sums of squares. Standard errors and differences between treatments were determined from the PDIFF option, where $P \leq 0.05$ was required to be significant.

The model statement for $\log_{10}(Pm + 1)$ and yield was irrigation rate (IR), CHEM, and IR × CHEM. The random statement contained year, REP (year), REP × IR (year), year × IR, and year × CHEM. With yield, the error between irrigation rates was different, so the three irrigation rates were analyzed across both years but analyzed separately by irrigation rate. The random statement in this case was year, REP (year), and year × CHEM. Differences were considered significant at $P \leq 0.05$, using the PDIFF option with LSMEANS.

Environmental variables affecting chemical treatments in TX: From 2004 to 2010, a series of small- and large-plot nematicide experiments was conducted near Lamesa, TX, in a field with an Amarillo sandy loam (fine-loamy, mixed, superactive, thermic, Aridic Paleustalf), pH = 7.8, and 80% sand, 3% silt, 17% clay, and 0.2% organic matter. Nematicide treatments included an untreated control that was present in 15 of 20 tests; an insecticide seed treatment (thiamethoxam, 0.34 mg ai/seed, Cruiser® 5FS, Syngenta, Greensboro, NC), which was present in 8 of 20 tests; a nematicide/insecticide seed treatment (NST), which was present in 14 of 20 tests; and aldicarb at 0.84 or 0.59 kg ai/ha, which was present in 17 of 20 tests. The two nematicide/insecticide seed treatments were Aeris and Avicta® Complete Cotton (abamectin (0.15 mg ai/seed), thiamethoxam (0.34 mg ai/seed), and three fungicides (azoxystrobin at 0.002 mg ai/seed, fludioxonil at 0.0003 mg ai/seed, and mefenoxam at 0.001 mg ai/seed), Syngenta, Greensboro, NC.) Treatments with other combinations like NST + aldicarb or experimental compounds, formulations, or other rates were deleted from the analysis because they were present in only four or fewer data sets. Data included in the analyses were galls/root, $\log_{10}(Pm + 1)$, and yield (kg lint/ha).

Large-plot trials were conducted similarly to the two trials reported above. Small-plot trials were in 10.7-m-long rows, two or four rows wide, in randomized complete block designs with four to eight replications. Gall ratings were made on 10 plants/plot, and midseason nematode samples were taken at five locations/plot. Both eggs and J2 were extracted as described previously. Pm was calculated as described previously. Plots were machine harvested with a two-row cotton stripper that contained a cage on load cells inside the stripper basket to catch the plot yield. Samples were taken of harvested cotton and ginned as described previously.

A weather station on-site recorded environmental parameters including rainfall, air temperature, solar radiation, humidity, and wind. Maximum and minimum daily air temperatures were used in calculation of heat units. Solar radiation, humidity, and wind and air temperature were used in calculating reference ET (ETos) based on the ASCE Standardized Reference Evapotranspiration (ET) equation, grass (short crop, ETos) reference (Allen et al., 2005; Marek et al., 2010). Irrigation amounts applied through the center pivot system were recorded. Weather information was either averaged (temperature, ETos, heat units) or summed (water) for each month. Cumulative water and heat units were also calculated for each month.

Analysis of TX data: Effect of chemical treatments (CHEM) on root galling, $\log_{10}(Pm + 1)$, and yield were analyzed over the entire 20 experiments as a group, using Proc Mixed, SAS Version 9.3. The treatments were untreated check; insecticide check; NST; and aldicarb. The two NST treatments (Aeris and Avicta Complete Cotton) were compared to see if significant differences ($P < 0.10$) existed, and then treated as equivalent, because of no significant treatment differences. Different rates of aldicarb were also compared for significant differences ($P < 0.10$), and then treated as equivalent, because of no significant treatment differences.

The model statement initially had treatment alone (CHEM), and the random statement was trial, REP (trial), and trial × CHEM. The Satterthwaite option was used as discussed previously. Additional analyses were then conducted with the monthly averages or sums of environmental variable (EV) used as covariates. All covariates used in the model were actually the covariate value minus the mean value across all data sets (Draper and Smith, 1981). Since gall ratings were made in early to mid-June, only EV in May was applied to that analysis. All EV were considered as covariates for Pm and yield and were examined as linear factors and as interactions with CHEM. The model chosen required CHEM to be significant at $P < 0.10$ and the EV at $P < 0.10$, though preference was given to models that were significant at $P < 0.05$.

To calculate the individual contribution that CHEM and EV made to the overall model, Proc GLM (SAS Institute) with type I sum of squares was used. The ratio of the type I sum of squares for CHEM and EV (in that order) were divided by the total sum of squares to calculate R^2 of each variable.

Environmental variables and nematicide tests in AL: A total of 12 data sets with 34 observation means were collected between 2004 and 2010. A series of small-plot nematicide experiments was conducted near Tallassee, AL, on the Plant Breeding Unit of the E. V. Smith Research Center in a field with a Kalmia loamy sand (fine-loamy over sandy or sandy-skeletal, siliceous, semiactive, thermic Typic Hapludults,), pH = 6, 80% sand, 10% silt, 10% clay, and 0.5% organic matter. All tests were arranged in a randomized complete block design with 5 replicates. The chemical treatments varied by test but included: an untreated check, aldicarb at 0.59 and 0.84 kg ai/ha (i.f. at-plant), oxamyl at 0.28 kg ai/ha (6 to 8 leaf stage), and NST. All tests were planted between 11 and 27 April with the cultivar DPL555 BGRR (BG is BollGuard I and RR is Roundup Ready (Delta and PineLand, Scott, MS)). An untreated check was included in all tests, NST were included in six tests, aldicarb was included in 10 tests; and the combination of NST, aldicarb, and oxamyl (NST/A/O) was included in six tests. Oxamyl was banded over the top of plants at the 6 to 8 leaf stage. The application was made using a CO_2 back pack sprayer equipped with a 1.8-m boom with four 80015 flat fan nozzles calibrated at 172 kpa and 4.8 km/h to apply 15.3 L/ha.

Nematode eggs were extracted from root systems at 60 d after planting (Pm). Three plants were excavated from each plot; roots were removed, washed gently, and weighed; and eggs were extracted with sodium hypochlorite (Hussey and Barker, 1973). Plots were machine harvested with a two-row cotton picker and seed plus lint represented yield. A weather station on site recorded environmental parameters.

Analysis of AL data: Due to the limited number of observations (because means were used rather than individual plot observations), the analysis was conducted with Proc GLM (SAS Institute), using the model statement: Yield = CHEM EV Test. An additional analysis was run using just CHEM and EV (removing Test) to determine the individual contribution of each of those variables. The calculation of R^2 and significance levels were the same as in the TX data. EV that were considered in the model were heat units in April, May, June, July, and August; cumulative heat units in each month; rainfall for each month; and cumulative rainfall for each month. $\log_{10}(\text{Pm} + 1)$ was also examined as a covariate. Rules for accepting a covariate were the same as with the TX data (all variables had to be significant at $P < 0.10$). To determine whether there was an impact of root-knot nematode on yield, independent of chemical treatment, Yield = $\log_{10}(\text{Pm} + 1)$ was also analyzed.

Results

Nematicide/Irrigation rate experiment in TX: Crop evapotranspiration (ET) and water applied to the test (rainfall plus irrigation) were similar in May in both 2009 and 2010 (Fig. 1). Water applied to the test area was slightly below crop ET in June in both years; however, in July 2009, there was severe water stress during July and August, compared to 2010, where there was excessive water in July (Fig. 1). So 2009 can be characterized as dry, especially during the flowering and boll-filling stages; while 2010 was wet during the flowering time, though there may have been some water stress during the boll-filling time in August.

Chemical effects on root galling at approximately 35d after planting were not significant (Table 1). There were no significant irrigation or chemical effects on $\log_{10}(\text{Pm} + 1)$ (Table 1).

Yield increased as irrigation rate increased (average of 1,079, 1,307, and 1,428 kg lint/ha for B - 33%, B, and B + 33%, respectively). Variance for yield was different between the irrigation rates, so it was necessary to run the chemical treatment analysis for each irrigation rate separately. Chemical treatment affected yield only at the B irrigation rate (Table 1), where the untreated check had lower yields than treatments with aldicarb at 0.59 kg ai/ha, and NST treatments. There were no significant differences between chemical treatments with the B - 33% or B + 33% irrigation rates (Table 1).

Environmental variables affecting nematicide performance in TX: Root galls as a function only of CHEM was significant at $P = 0.085$; however, when water in May was added as a covariate interacting with CHEM, then both CHEM and the covariate were highly significant ($P < 0.001$) (Table 2). Aldicarb had fewer galls/root system than did any other treatments when water in May was used as a covariate that interacted with treatment (Table 2). The dynamics of both aldicarb and NST were similar, with galls/root being reduced as water in May increased (slope = -0.30 reduction in galls/cm water in May for both treatments) (Fig. 2). Galls/root increased as water in May increased for both the untreated check

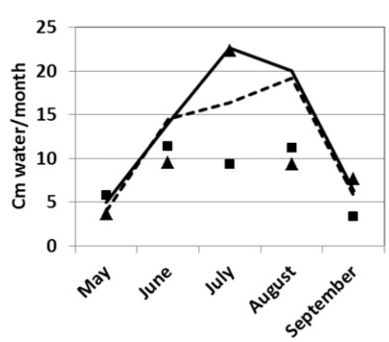

Fig. 1. Crop evapotranspiration for 2009 (———) and 2010 (- - - - -) and rainfall combined with irrigation applied in 2009 (■) and 2010 (▲).

TABLE 1. Effect of nematicide treatments (CHEM) on root galls caused by *Meloidogyne incognita* (RK), midseason nematode density, and yield with three irrigation rates.

			Yield (kg lint/ha)		
			Irrigation rate[3,4]		
CHEM[1]	Galls$^{1/2}$/root	$\log_{10}(Pm + 1)^2$	B - 33%	B	B + 33%
CK	3.36 a[4]	3.26 a	1,084 a	1,183 b	1,423 a
A = 0.59	3.06 a	3.29 a	1,053 a	1,348 a	1,462 a
A = 0.84	3.21 a	3.35 a	1,135 a	1,288 ab	1,440 a
NST	3.51 a	3.09 a	1,033 a	1,393 a	1,345 a
NST + A = 0.84	3.19 a	3.17 a	1,092 a	1,325 a	1,458 a
	Model F-tests, standard error, and degree of freedom				
Prob > F (CHEM)[4]	0.24	0.070	0.756	0.017	0.679
Prob > F (Water)	–	0.425	–	–	–
Prob > F (Water × CHEM)	–	0.548	–	–	–
SE_{CHEM} – NST	1.46	1.55	147.9	146.6	127.7
SE_{CHEM} + NST	1.47	1.81	158.0	151.8	137.8
DF_{CHEM}-NST	1.0	1.65	1.2	1.1	1.2
DF_{CHEM}+NST	1.0	3.0	1.5	1.3	1.7

[1] CK = the nontreated check (no nematicides or insecticides); A = aldicarb, rate is in kg ai/ha at-planting; NST is the seed treatment nematicide containing thiodicarb + imidacloprid, both at 0.375 mg ai/seed.
[2] Pm is root-knot nematode density/500-cm^3 soil.
[3] Base (B) refers to the base irrigation rate. The other two irrigation rates were 33% above or below the base irrigation rate.
[4] Means within a column followed by the same letter are not significantly different at $P = 0.05$. Means were not compared across columns because in the case of galls/root or RK, there was no significant irrigation or interaction affect. In the case of Yield, variances were different between irrigation rates, so each irrigation rate was analyzed separately. Standard errors (SE) and degree of freedom (DF) were the same for all treatments within a column except NST, which was only tested in 2009.

(slope = 0.36 galls/cm water) and the insecticide seed treatment (slope = 0.18 galls/cm water) (Fig. 2). No other EV in May was significant for root galls. The full model, which included trial, CHEM, and water in May (CHEM) explained 56% of the variation in galls/root ($R^2 = 0.56$). CHEM and EV had partial R^2 of 0.093 and 0.083, respectively.

Chemical treatments did not affect yield when no covariates were included in the model for TX ($P > 0.99$) (Table 3). There were a number of EVs that were significant at $P < 0.05$ where CHEM was significant at $P < 0.10$. In all of these models, aldicarb treatment resulted in significantly higher yields ($P < 0.02$) than the nontreated controls, and yield of the insecticide seed treatments and NST were intermediate (Table 3). Most of these EV were related to temperature (average high temperature in August, average low temperature in August, heat units in August, cumulative heat units in August, average low temperature in July, and cumulative heat units in July) and only one was related to water (May). The least squares mean CHEM values changed slightly depending on which EV was used, but the relationship between CHEM was similar in all of these analyses. All of these EV except water in May had a negative relationship with yield, i.e., the higher the temperature, the lower the yield. For water in May, higher values were associated with higher yield. None of these EV interacted with CHEM; however, inclusion of these variables resulted in a change in significance

TABLE 2. Effect of chemical treatments (CHEM) and cumulative water in May as a covariate (COV) on galls/root system in Lamesa, TX (2004–2010).

	Galls/root			Galls/root		
CHEM[1]	No COV	SE[2]	DF[2]	COV	SE	DF
Check	10.4 a[3]	1.9	20.5	10.9 a	1.7	15.4
I	9.8 ab	2.1	30.8	9.8 a	1.9	23.9
NST	10.8 a	1.9	19.8	10.9 a	1.7	15.7
Aldicarb (A)	7.7 b	1.8	18.6	7.1 b	1.7	14.4
Prob. > F (CHEM)	0.085			0.001		
Prob. > F (COV)				0.001		

[1] Check contained no nematicide or insecticide; I = an insecticide-only seed treatment check. NST = nematicide plus insecticide seed treatment that included either thiodicarb or abamectin.
[2] SE = standard error; DF = degrees of freedom.
[3] Means within a column followed by the same letter are not significantly different at $P = 0.05$.

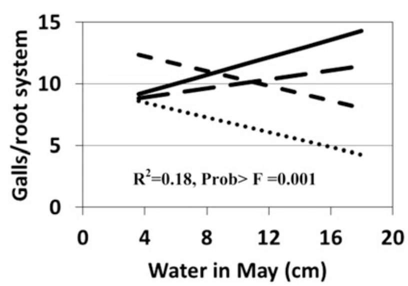

FIG. 2. The effect of nematicide treatments as they interacted with cumulative water in May on number of galls per root at 35 d after planting in TX. Treatments (CHEM) were: untreated check (CK) (———), insecticide seed treatment (I) (—— ——), nematicide seed treatment (NST) (— — —), and aldicarb (A) (•••••••). Equations were calculated for galls/root = CK = 10.8 + (0.36 × (water in May (cm) – 8.20); I = 9.7 + (0.18 × (water in May (cm) – 8.20); NST = 11.0 – (0.30 × (water in May (cm) – 8.20); A = 7.2 – (0.30 × (water in May (cm) – 8.20). CHEM $R^2 = 0.09$ (Prob. > F = 0.001) and cumulative water in May $R^2 = 0.08$ (Prob. > F = 0.001).

TABLE 3. Analysis of chemical treatment[1] on cotton yield (lint) in a field in TX from 2004–2010 when various environmental parameters[2] were also included in the model.

Parameter[2]	Estimate[3]	SE	R^2	Prob. > T[3]	Mean CK[1]	SE	Mean I[1]	SE	Mean NST[1]	SE	A	SE
CHEM (C)			0.012	0.999	1,525 a	18,192	1,556 a	20,248	1,537 a	17,954	1,573 a	17,694
C + AHT	−49.9	18.9	0.328	0.017	1,555 b	64	1,609 ab	69	1,584 ab	64	1,626 a	63
C + AHU	−87.8	28.0	0.391	0.006	1,556 b	60	1,609 ab	66	1,584 ab	60	1,627 a	59
C + ALT	−124.3	46.6	0.330	0.016	1,525 b	62	1,579 ab	67	1,553 ab	62	1,597 a	61
C + ACHU	−1.0	0.3	0.375	0.003	1,529 b	57	1,583 ab	63	1,558 ab	57	1,602 a	56
C + JLT	−255.8	59.7	0.478	0.001	1,546 b	53	1,600 ab	59	1,574 ab	53	1,618 a	52
C + JCHU	−0.9	0.4	0.228	0.030	1,514 b	63	1,567 ab	69	1,542 ab	63	1,586 a	62
C + MW	68.3	32.4	0.168	0.050	1,516 b	65	1,567 ab	70	1,543 ab	65	1,588 a	64

[1] Chemical treatments included an untreated check (CK), an insecticide check (I), a nematicide seed treatment (NST), and aldicarb (A) A total of 20 tests were used in the analysis with 597 observations.
[2] Environmental parameters were abbreviated so that A = August; HT = average high temperature for that month; HU = heat units for that month; LT = average low temperature for that month; C = cumulative; ET = evapotranspiration rate; and W = water (rainfall + irrigation) for that month. The parameters used in the model were actually the parameter value minus the mean of the parameter value.
[3] Proc MIXED also was used with the Satterthwaite option to determine degrees of freedom, and the solution option to fit a parameter to the environmental variable. CHEM means were determined with the least squares means option, and significant differences with the PDIFF option. Proc GLM was used to calculate R^2 value. Mean treatment values represent the least square means.

between CHEM treatments (i.e., $P > 0.99$ for no environmental variables versus P typically = 0.08 with inclusion of EV).

The partial R^2 value for CHEM and trial in the models (Yield = CHEM EV trial), was 0.012 and 0.73, respectively. The partial R^2 of an EV ranged from a low of 0.17 for water in May to a high of 0.48 for average low temperature in July. Yield was strongly affected by environment and CHEM impact was low with or without environmental variables. The increase in yield over the untreated check without EV was 2.0%, 0.8%, and 3.1% for insecticide seed treatment, NST, and aldicarb respectively, and with the inclusion of average high temperature in August for example, were 3.5%, 1.9%, and 4.6%, respectively (Table 3).

The midseason population density of root-knot nematode in TX was not affected by chemical treatment. There was no EV that could be included in the model that would change this relationship.

Environmental variables affecting nematicides in AL: CHEM affected yield in AL when the term trial was used to represent the error associated with each individual trial (Table 4) and without the inclusion of EV. The average yield (seed plus lint weight/ha) was higher for plots treated with NST/A/O (2,715 kg/ha) than for plots with the untreated check (2,204 kg/ha) and NST (2,221 kg/ha). Aldicarb treated plots were intermediate (2,441 kg/ha) (Table 4).

A number of environmental parameters met the criterion to be included in a model including cumulative

TABLE 4. Analysis of the effect of chemical treatment[1] and environmental parameters[2] or root-knot nematode density ($\log_{10}$ transformed (LPM)) at 60 days after planting, on cotton yield (seed + lint) in a field in AL from 2004–2010.

Parameter	Estimate[3]	SE	R^2	Prob. > T[3]	Mean CK[1]	SE	Mean NST[1]	SE	Mean A[1]	SE	Mean NST/A/O[1]	SE
Trial			0.90		2,204 b	88	2,221 b	138	2,441 ab	101	2,715 a	139
WCM	61.2	15.9	0.44	0.001	2,147 b	172	2,211 b	246	2,291 b	188	2,925 a	242
WCJn	45.9	12.6	0.42	0.001	2,143 b	175	2,196 b	251	2,293 b	192	2,944 a	247
WCJl	21.9	7.8	0.33	0.009	2,151 b	187	2,132 b	266	2,298 ab	205	2,983 a	265
WCA	16.4	5.3	0.36	0.005	2,152 b	184	2,134 b	260	2,292 b	201	2,991 a	260
DM	−13.7	3.5	0.44	0.001	2,168 b	170	2,108 b	241	2,299 b	187	2,974 a	241
DJn	−14.7	3.5	0.47	0.001	2,167 b	167	2,136 b	237	2,270 b	184	2,996 a	237
DA	−12.5	2.2	0.59	0.001	2,141 b	147	2,224 b	210	2,324 b	161	2,868 a	207
CDJu	−5.9	1.9	0.37	0.003	2,156 b	182	2,133 b	258	2,281 b	199	3,004 a	258
CDA	−4.7	1.1	0.50	0.001	2,140 b	162	2,188 b	232	2,286 b	178	2,969 a	229
DA(Trt)[4]			0.59		2,135 b	155	2,260 ab	255	2,326 ab	169	2,873 a	218
CDA(Trt)[4]			0.51		2,144 b	170	2,105 b	318	2,286 b	186	3,014 a	247
LPm	−382	139	0.32	0.010	2,253 b	188	2,021 b	265	2,243 b	209	2,984 a	267

[1] Chemical treatments included an untreated check (CK), a nematicide seed treatment (NST) which was Avicta® Complete Cotton, aldicarb (A) applied in the furrow at planting (A), and a combination of NST and A at planting and oxamyl banded over the top of plants at 6-8 leaf stage. A total of 12 tests were used in the analysis with 34 mean observations.
[2] Environmental parameters were abbreviated so that W = water; C = cumulative (as opposed to monthly sum); M = May; Jn = June; Jl = July; A = August; D = degree-days (base of 15.6°C). The parameters used in the model were actually the parameter value minus the mean of the parameter value. Proc GLM was used to fit chemical treatment and environmental parameter, and the solutions option provided the parameter estimate and standard error. Mean treatment values represent the least square means.
[3] The parameter estimate and standard error (SE), and probability > 0 with a t-test.
[4] DA and CDA interacted with chemical treatment. For DA individual slopes and standard errors (SE) were −13.7 (3.6), −14.8 (8.6), −11.3 (4.3), and −10.7 (5.4) for CK, NST, A, and NST/A/O, respectively. Slopes were not significantly different between treatments. For CDA individual slopes and SE were −4.5 (1.6), −2.2 (6.4), −4.7 (1.7), and −7.8 (4.4) for CK, NST, A, and NST/A/O, respectively. Slopes were not significantly different between treatments.

water in May, cumulative water in June, cumulative water in July, cumulative water in August, degree-day in May, degree-day in June, degree-day in August, cumulative degree-day in June, cumulative degree-day in August, the interaction between degree-day in August and CHEM, and the interaction between cumulative degree-day in August and CHEM. With the inclusion of any of these parameters in the model except cumulative water in July or degree-days in August interacting with CHEM, the result of the EV was to significantly separate the NST/A/O treatment from all other treatments (Table 4).

Yield was reduced as temperature increased for all the temperature related EV, or yield was increased as water increased for water type EV (Table 4).

Discussion

One objective of this project was to determine how or if environmental variables affected the efficacy of nematicides. Irrigation rate was manipulated to create three different environments within the same test and the impact on nematicide treatment was examined. Cotton yield was affected by nematicide treatments only at the moderate irrigation rate, whereas there was no significant impact of nematicide treatments at the lower or higher irrigation rate. The manipulation of environment did not start until after root galling was evaluated, so no difference in root galls, attributed to environment, could be examined in the controlled nematicide/irrigation rate experiment.

When a number of experiments over many years were evaluated, there was a clear difference between behavior of nematicide treatments (NST and aldicarb) versus treatments that did not contain nematicides, with respect to root galls. As moisture increased during the month of planting, the nematicide treatments caused a reduction of galls/root system. The exact opposite occurred with the nonnematicide treatments, where there was an increase in galls as moisture increased. The increase in galls could have been a function of improved nematode hatch, mobility, and infection, or even that a higher percentage of the root system (particularly of finer lateral roots) was obtained from the field plots, relative to the drier years where fine roots are often left in the soil. Soil moisture improved the performance of both nematicide seed treatments and aldicarb on root galling. The nematicide seed treatments were unable to match the level of control provided by aldicarb, at any moisture level encountered in the study. Even under relatively dry conditions, aldicarb provided for much better control than did the seed treatment nematicides. Seed treatment nematicides reduced galls/root system better than nonnematicide products only under very high levels of moisture. Including environmental parameters provided a better understanding of how and why performance of nematicides changes from year to year than just comparing mean gall values across the tests.

The method of evaluation for early season root-knot nematode infection from the AL data sets was slightly different than the TX data sets. For the AL tests, early season nematode reproduction (eggs at 60 d after planting) was used to evaluate the success of nematicide treatments. It is interesting that environmental conditions did not appear to influence early season nematode reproduction in AL, when they did affect early season root galls in TX. Galls/root system would likely be a less precise measure of early-season nematode infection and successful development of root-knot nematode females than a direct measurement of first-generation egg production. However, using galls/root system to evaluate nematicide efficacy was more successful in these analyses than using early-season nematode reproduction, or chemical treatment performance differed substantially between the two locations.

Yield is determined by a number of factors during the growing season and does not necessarily correlate with gall ratings, though it was negatively affected by eggs of root-knot nematode at 60 d after planting in AL. The root-knot nematode population was moderate in TX and ranged from low to very high in AL. However, more damage was expected in AL because the field was co-infested with *Fusarium oxsporum* f. sp. *vasinfectum*. The chief method of managing Fusarium wilt in cotton is by management of the root-knot nematode, which interacts with *F. oxysporum* (Colyer et al., 1997). There was a significant and negative relationship between root-knot nematode density and yield at the AL site that was independent of chemical treatment (Table 4). The TX field had no significant fungal diseases present during the 7-yr study. The overall yield increase in TX with aldicarb in the presence of root-knot nematode averaged 3 to 5% over the untreated check, while in AL, and in the presence of Fusarium wilt/root-knot nematode complex it was approximately 10%. That the response to aldicarb was significant at $P = 0.05$ in TX with the inclusion of some environmental parameters and not significant in AL may be a function of degrees of freedom, since individual observations were used in TX (597) versus means (34) in AL. The treatment with the largest impact on yield was a combination of nematicide seed treatment, aldicarb, and oxamyl. This treatment was only tested in AL. In both AL and TX, water related environmental variables were positively correlated with yield while temperature related parameters were negatively associated with yield.

The two fields also differed in environmental parameters (Table 5). The heat units during July and August were lower in TX than in AL, which was due in part to the cooler night time temperatures found in the Southern High Plains of TX. Moisture averaged about 53 cm in AL from April to August, and 46 cm in TX from May to August (Table 5). The range for moisture

Table 5. Environmental variables (low, high, and average) for months during the cotton growing season) in Alabama[1] and Texas[1].

	Rainfall + irrigation (cm)						Heat units (DD 15.6 Base)					
	Alabama			Texas			Alabama			Texas		
Month	Low	High	Av	Low	High	Av	Low	High	Av	Low	High	Av
April	3.7	19.1	7.6	–	–	–	23	93	48	–	–	–
May	0.9	25.1	11.9	3.6	18.2	8.2	157	257	215	128	257	204
June	2.4	10.0	5.4	3.8	13.5	10.3	271	367	336	260	365	326
July	4.8	22.7	12.1	8.3	22.3	13.2	335	413	378	298	384	332
August	3.8	25.9	16.0	9.3	18.0	13.0	348	456	406	269	358	314

[1] A weather station was used to collect the environmental data at both research sites (AG-CARES Research Farm in Lamesa, TX; and on the Plant Breeding Unit of the E. V. Smith Research Center, Tallassee, AL.

tended to be both higher and lower in AL than in TX. The AL site was not irrigated while the TX site was deficit irrigated (irrigated less than full crop water demand). Water stress in TX might be more consistent of a factor than in AL but may not have reached the extremes that could occur in AL. The two sites were compared for responses to determine how universal an environmental parameter might be to yield in root-knot nematode fields. The general trend that occurred was that higher temperatures led to lower yields. While that may also be typical in nonroot -knot nematode fields, it may lead to greater damage in root-knot fields.

The galls that disrupt the xylem and cortical tissue may also affect water uptake. Healthy cotton (without root-knot nematodes) used 184% more water than did cotton infected with root-knot nematode, when soil moisture was allowed to fluctuate between 50% and 100% of field capacity; whereas, when soils were kept constantly at field capacity, both root-knot infected and healthy plants used the same amount of water (O'Bannon and Reynolds, 1965). Wheeler et al. (1991) found that more relative yield was lost per root-knot nematode, as water stress or nutrient stress increased. Kirkpatrick et al. (1995), found that the rate of water flowing through cotton plants during a 24-hr period in field microplots, was lower for root-knot nematode infected plants than for healthy plants, and that aldicarb could moderate some of the negative effects of root-knot nematode. In both sites, yield was positively related to moisture and negatively related to temperature, which may have been a function of water stress associated with nematode damage. Aldicarb resulted in significantly higher yields in TX and trended in that direction in AL compared to either the nontreated check or nematicide seed treatments when temperature parameters were included in the model to describe yield.

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