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Comparison of Variable and Single-Rate Applications of Aldicarb on Cotton Yield in Fields Infested with *Meloidogyne incognita*

T. A. Wheeler,[1] H. W. Kaufman,[2] B. Baugh,[3] P. Kidd,[4] G. Schuster,[5] and K. Siders[6]

Abstract: Variable-rate applications of the nematicide aldicarb were compared to producer standard rates in eight field tests over 3 years. Test areas (308 to 1,015 m long) were divided into eight or five blocks. Each block contained two plots with a variable-rate treatment (VRT) of aldicarb and a producer standard treatment (PST) of aldicarb. Each VRT plot was divided into three subunits and intensively sampled for *Meloidogyne incognita* in either the fall or spring before planting. Rates of aldicarb were assigned to each subunit for VRT based on *M. incognita* population density. In three of the eight tests, VRT resulted in either higher yield or similar yields, but less nematicide applied. In two tests there were no differences between PST and VRT in yields or average rates of aldicarb applied. In three tests, VRT used more aldicarb (>0.17 kg a.i./ha difference) than PST and yields were not significantly different between treatments. In two of the cases where VRT was superior to PST, the producer's rate of aldicarb was judged to be either too low or too high for the average *M. incognita* density present in the field. In all three cases where PST was superior to VRT, perennial weeds were an important factor also limiting yield. Variable-rate application of aldicarb did not consistently provide for higher yields or lower nematicide usage than standard application rates.

Key words: aldicarb, control, cotton, *Gossypium hirsutum, Meloidogyne incognita,* nematicides, nematode, precision agriculture, root-knot nematode, variable-rate application.

Current management of *Meloidogyne incognita* (southern root-knot nematode) on cotton relies primarily on crop rotation (Johnson et al., 1974; Johnson et al., 1998; Kirkpatrick and Sasser, 1984), use of root-knot nematode-resistant cultivars (Klump and Thomas, 1987; Ogallo et al., 1997; Robinson and Percival, 1997), and nematicide application (Johnson et al., 1998; Jorgenson, 1979; Thomas and Smith, 1993). Rotation of cotton with peanut can be beneficial for cotton yields (Kirkpatrick and Sasser, 1984; Johnson et al., 1998) but cannot be used on all root-knot nematode-infested cotton fields due to the vast hectarage of cotton compared with peanut. In Texas, which is ranked first and second nationally in land area planted to cotton and peanut, cotton is planted on 18 times more hectares than peanut (Texas Agricultural Statistics Service, 1997). Recently released cotton cultivars with resistance to *M. incognita* (Acala NemX and Stoneville LA887) can reduce yield losses due to root-knot nematode, but neither cultivar is adapted to the climate of west Texas. Consequently, cotton producers rely on nematicides such as aldicarb and 1,3-dichloropropene for management of root-knot nematodes.

Damage to plants caused by nematodes is generally related to the density of the nematode at planting (Oostenbrink, 1966; Seinhorst, 1965). In cotton, yield losses were associated with preplant *M. incognita* densities of 50 to 100 eggs/500 cm^3 soil (Starr et al., 1989). Sampling at planting to determine root-knot nematode density is less reliable, however, than sampling in the fall to predict densities for the following spring (Goodell, 1993), and the overwinter survival of root-knot nematode is unpredictable (Starr and Jeger, 1985). Overwinter survival of *M. incognita* in the west Texas area (Lubbock County) averaged 24% during one winter for a fall population of 300 *M. incognita*/500 cm^3 soil (Starr and Jeger, 1985). A fall mini-

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[1] Texas Agricultural Experiment Station, Rt. 3, Box 219, Lubbock, TX 79401.
[2] Texas Agricultural Extension Service, Rt. 3, Box 219, Lubbock, TX 79401.
[3] Texas Agricultural Extension Service, 1418 Ave. G, Lubbock, TX 79401-1039.
[4] Texas Agricultural Extension Service, 209 South 5th St., Brownfield, TX 79316.
[5] West Texas A&M University, IPM, Division of Agriculture, Box 60998, Canyon, TX 79016-0001.
[6] Texas Agricultural Extension Service, 1212 Houston St., Suite 2, Levelland, TX 79336.
E-mail: ta-wheeler@tamu.edu
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mum damage threshold of 208 to 416 *M. incognita*/500 cm^3 soil could be estimated based on a minimum preplant damage threshold of 50 to 100 *M. incognita*/500 cm^3 soil coupled with a 24% overwinter survival rate.

Cotton production has experienced increasing costs, low prices for lint, and insufficient demand, forcing producers to grow cotton more efficiently. The agrichemical industry is facing the challenge of developing safer pesticides with low application rates, and recommending lower rates of labeled materials. All currently labeled chemical nematicides are highly toxic materials that are applied at high rates compared to insecticides. Reduction in the quantity of nematicides used in cotton production should reduce potential risks to the environment and to human health.

The challenge of lowering cotton production costs and reducing pesticide usage for root-knot nematode control may be partially resolved by variable-rate application of nematicides. Currently, nematicides are applied at a single rate across an entire field regardless of the variation in nematode population density. Root-knot nematodes are known to be spatially aggregated (Goodell and Ferris, 1980; Noe and Campbell, 1985; Wheeler et al., 1994). If fields can be reduced to subunits with similar nematicide rate needs, then total nematicide use may be reduced. The objective of this study was to determine if variable-rate application of nematicides was more beneficial in terms of yield and (or) reduction in nematicide rate than standard producer rates of nematicide in root-knot nematode-infested test sites.

Materials and Methods

During 1996 and 1997 test areas in five sites, designated fields 1–5 (Table 1) were divided into eight blocks, and in 1998 test areas in three sites (6–8) were divided into five blocks. Each block contained two treatments: a variable-rate application of aldicarb (VRT), which was based on root-knot nematode density obtained from intensive sampling of soil; and the producer standard rate of aldicarb (PST). The PST varied from field to field, ranging from 0.41–0.83 kg/ha. Treatments were applied over either four-row or eight-row plots, arranged in a randomized complete block design. The order of the PST and VRT plots in each block was selected with a random number generator (PROC PLAN, SAS Institute, Cary, NC) in each block. Each VRT plot was sampled in either the fall (fields 3–7) or spring (fields 1, 2, and 8) before planting. Most VRT plots were divided equally into three subplots, and two composite soil samples for nematode assay were collected from each subplot. For fields 1–6, soil samples were also taken for each subplot of the PST plot, and root-knot nematode density was compared with

Table 1. Field test locations, year of test, cultivars, plot length, aldicarb (kg a.i./ha) rate, and *Meloidogyne incognita* (Mi) average density (Mi per 500 cm^3 soil) for eight nematicide tests conducted from 1996 to 1998.

Field	County	Year	Plot row length (m)	Cultivar planted	Aldicarb rate PST[a]	Aldicarb rate VRT[b]	Mi[d]
1	Lamb	1996	308	PM[c]HS-26	0.83	0.41–0.83	46
2	Gaines	1996	812	PM HS-26	0.58	0.58–1.16	604
3	Hockley	1997	383–576	PM HS-26	0.41	0.58–1.16	1,030
4	Lubbock	1997	354–716	PM 2326RR	0.83	0.58–0.83	797
5	Lamb	1997	812	PM HS-26	0.50	0.41–0.83	641
6	Terry	1998	997–1,015	PM 2326RR	0.67	0.50–1.16	1,483
7	Hockley	1998	441–785	PM 2326RR	0.50	0.50–1.0	2,832
8	Lubbock	1998	369	PM 2200RR	0.50	0.50–1.0	543

[a] PST: producer standard rate.
[b] VRT: variable-rate treatment.
[c] PM: Paymaster cotton seed.
[d] Fields 1, 2, and 8 were sampled in the spring, while the other fields were sampled in the fall.

the VRT plots. Actual nematicide rates for the VRT subplots were assigned based on mean nematode density for that subplot (Table 2); thus, subplots within a plot received variable nematicide rates. Each plot was divided equally into thirds, except for fields 6 and 7. At field 6, the test area was divided into three subunits of unequal length, based on soil texture dissimilarities. At field 7, each plot was divided into equal subplots, but the number of subplots increased with increasing plot length (3 subplots for block 1; 4 subplots for blocks 2 to 4; and 5 subplots for block 5). Individual details about each test site (location, year, plot length, cultivar, and aldicarb rates) are presented in Table 1.

Composite soil samples consisted of 20 subsamples (approximately 50 cm^3 of soil/subsample), to a depth of 20 cm with a narrow-bladed shovel, removing only the soil from the 10- to 20-cm depth. Nematode population density from two composite samples taken from each subunit were averaged to minimize sampling error within a subunit. Second-stage juveniles (J2) were extracted from 200 cm^3 of soil (Thistlethwayte, 1970). Eggs were extracted by adding 2 liters of water to 500 cm^3 of soil + root fragments, stirring for 15 seconds, and allowing 15 seconds for settling before pouring the water + organic matter over a sieve with a 0.23-mm-pore opening. The eggs were extracted with chlorine bleach from the residue collected on the sieve (Hussey and Barker, 1973).

The PST rates were selected by the producers as normal usage rates at those sites and ranged from 0.41 to 0.83 kg a.i./ha. The VRT rates were based on *M. incognita* density at each subplot (Table 2). All nematicide applicators for each test belonged to each producer and were calibrated for the entire range of rates using an electric motor attached to the drive shaft of the planter (Ag-Products, Davis Junction, IL). Root-knot nematode-susceptible cultivars were planted at each site (Table 1). All fields were irrigated with center pivot systems with the exception of test 1, which was row (furrow)-irrigated before planting only. All plots except in field 8 were harvested with a cotton stripper, which was weighed at the end of each plot on portable scales (Evergreen Weight, Seattle, WA). At field 8, because of a severe infestation of woollyleaf bursage (*Ambrosia grayi*), the cotton was stripper-harvested at 15.4-m increments and weighed. The seed cotton weight for the entire plot was obtained by summing the weights from smaller increments, minus those plots that were heavily infested with woollyleaf bursage, and divided by the total (clean of weeds) area stripped. A subsample of harvested seed cotton plus trash was collected form each plot and ginned to determine percent lint, seed, and trash.

Weeds were mapped over the test area in all three test sites in 1998 (fields 6 to 8) with a differentially corrected global positioning system (DGPS), which included an Omnistar 7000 differential receiver (Omnistar, Houston, TX) and a March I/II global positioning hand-held unit and receiver (Corvallis Microtechnology, Corvallis, OR). Soil texture (five cores taken over an 8-m length at a depth of 10 to 15 cm) was determined at 29 georeferenced locations in field 7. Field 7 (1998) was at the same location as field 3 (1997). This site was repeated because of unusual results in 1997. An additional weed-infested field (field 8) was also selected in 1998 to further study variable-rate application in fields with other pest stresses.

Lint weight from each plot was analyzed for treatment differences (producer standard vs. variable-rate application) for all locations with analysis of variance (PROC GLM, SAS Institute, Cary, NC). Frequency histographs were created for *M. incognita* based on fall or spring population densities.

TABLE 2. Decision rules for variable-rate application of aldicarb to manage *Meloidogyne incognita* (Mi) in cotton.

Spring Mi/ 500 cm^3 soil	Fall Mi/ 500 cm^3 soil	Rate of aldicarb (kg a.i.;ha)
0–49	0–249	0.41–0.50
50–199	250–999	0.58
200–499	1,000–2,499	0.83
≥500	≥2,500	1.0–1.16

Results

The criteria for determining the best treatment (VRT vs. PST) in all tests were based on yield differences ($P = 0.05$) and reduction in rate of aldicarb. An average rate of aldicarb that differed at least 0.165 kg/ha was considered significantly different. In three tests VRT resulted in greater yields than PST and (or) reduction in nematicide usage. In two tests there were no significant differences in yield or nematicide usage between VRT and PST. In three tests VRT resulted in equal yields and significantly greater nematicide usage than PST (Table 3). Estimated population densities of root-knot nematicide in the VRT and PST plots did not differ in fields 1 to 6, where each plot was sampled separately in a block. Plots within a block were not sampled separately in fields 7 and 8.

At field 1, <30% of the test area had a density of *M. incognita* that exceeded the established damage threshold (Fig. 1A), and the average spring population density of 46 eggs + J2/500 cm^3 soil (Table 1) was less than the minimum damage threshold (50 *M. incognita*/500 cm^3 soil). The PST rate of aldicarb was 0.83 kg a.i./ha, which averaged 0.35 kg a.i./ha more aldicarb than VRT. There was no yield difference between treatments.

At field 2, the spring density of *M. incognita* averaged 604 eggs + J2/500 cm^3 soil (Table 1), and densities greater than threshold were found in 96% of the field (Fig. 1B). The producer applied 0.58 kg a.i./ha of aldicarb (PST), and VRT averaged 0.88 kg a.i./ha of aldicarb. The VRT plots averaged 217 kg of lint/ha more than the PST, a significant ($P = 0.05$) increase (Table 3).

At field 3, 87% of the test area had a density of *M. incognita* greater than the damage threshold (Fig. 1C). The average fall population density of *M. incognita* was 1,030 eggs + J2/500 cm^3 soil (Table 1). A low PST rate of aldicarb (0.41 kg a.i./ha) was applied. There was no yield difference associated with the higher rate of aldicarb imposed in VRT (Table 3). This field was infested with perennial weeds including woollyleaf bursage and Texas blueweed (*Helianthus ciliaris*).

At field 4, densities of *M. incognita* that exceeded the damage threshold covered 75% of the test area (Fig. 1D). The producer applied 0.83 kg a.i./ha of aldicarb on the PST (Table 3). Yields were not different between the two treatments, even though a lower average rate of aldicarb was applied with VRT than with PST (Table 3).

At field 5, *M. incognita* averaged 641 eggs + J2/500 cm^3 soil (Table 1), and densities greater than the damage threshold were found in 83% of the test area (Fig. 1E). The average rate of aldicarb was similar in both the VRT and PST (Table 3). Yields were not different between VRT and PST.

At field 6, the average *M. incognita* density based on fall sampling was 1,483 eggs + J2/500 cm^3 soil (Table 1) and densities of *M. incognita* greater than the damage threshold were found in 69% of the samples (Fig. 1F). This site had the smallest differences between the producer rate of aldicarb and the VRT, and yields were similar (Table 3).

At field 7, 90% of the test area was infested with *M. incognita* densities greater than the damage threshold (Fig. 1G) and average density (sampled in the fall) was 2,832 eggs + J2/500 cm^3 soil (Table 1). The producer rate of aldicarb was 0.50 kg a.i./ha, and the average VRT rate of aldicarb was 0.76 kg a.i./ha (Table 3). There was no significant difference in yield between VRT and PST plots. The proportion of each plot

Table 3. Influence of variable-rate (VRT) and producer standard rate (PST) of aldicarb on cotton yield.

		Aldicarb rate (kg a.i.;ha)		Yield (kg lint/ha)	
Field	Year	VRT	PST	VRT	PST
1	1996	0.48	0.83	883	791
2	1996	0.88	0.58	991[a]	774
3	1997	0.67	0.41	509	526
4	1997	0.64	0.83	901	882
5	1997	0.61	0.50	526	531
6	1998	0.76	0.66	787	760
7	1998	0.76	0.50	584	612
8	1998	0.84	0.50	868	864

[a] Significant ($P = 0.05$) difference in yield between VRT and PST treatments.

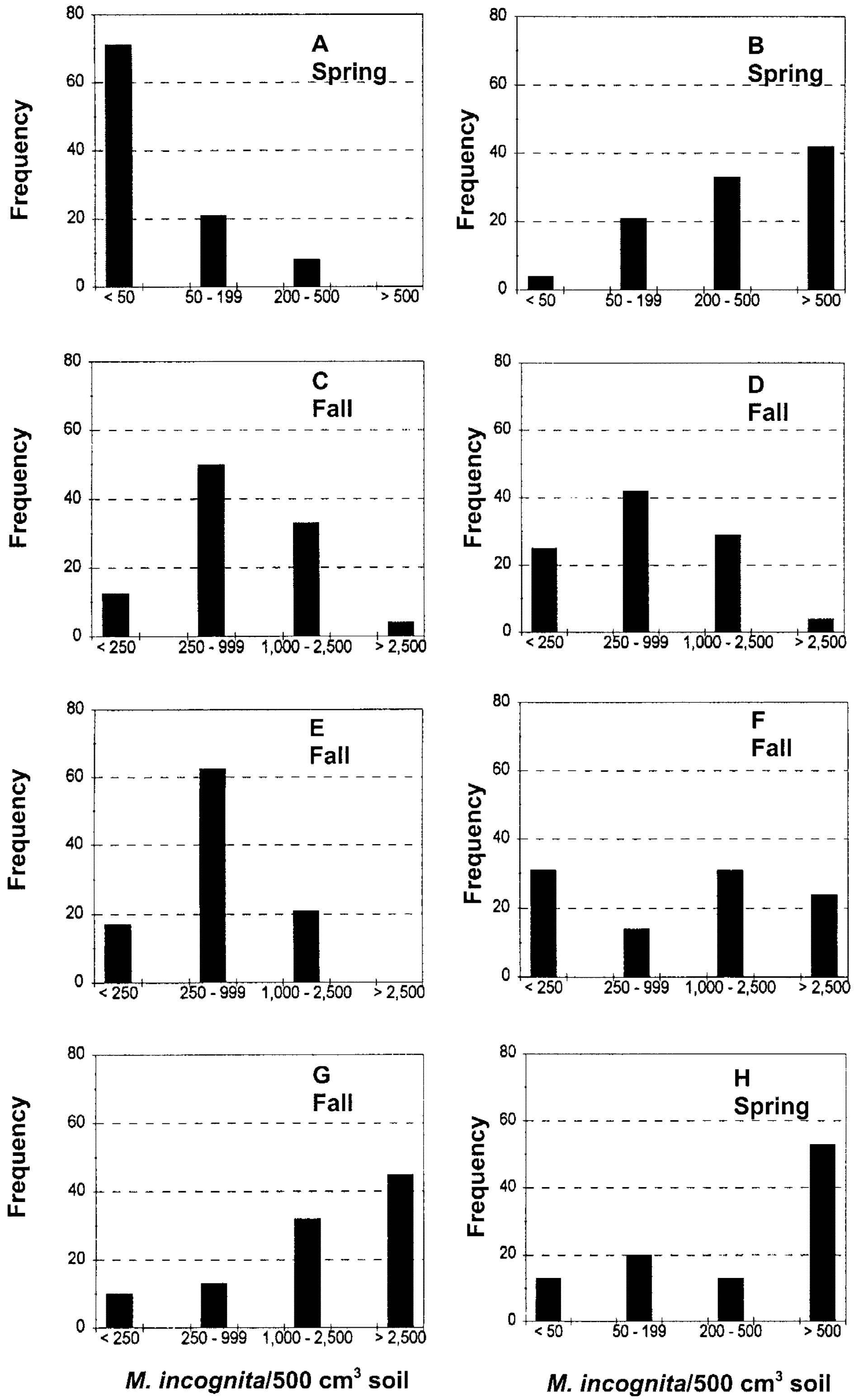

FIG. 1. Frequency histographs of *Meloidogyne incognita* population densities taken from eight fields during 1996-1998 in the spring or fall. A) Field 1. B) Field 2. C) Field 3. D) Field 4. E) Field 5. F) Field 6. G) Field 7. H) Field 8.

covered with woollyleaf bursage was negatively related to yield (Fig. 2A). There was a positive correlation between block number and yield at this site (Fig. 2B). There also was a negative relationship between block number and the proportion of the block affected with woollyleaf bursage (Fig. 2C) and a positive relationship between percent sand and proportion of a plot with woollyleaf bursage (Fig. 2D). *Meloidogyne incognita* population density was not correlated with percent sand, silt, or clay at this site.

At field 8, only 13% of soil assays indicated an *M. incognita* population density below damage threshold (Fig. 1H) and average density in the spring was 543 eggs + J2/500 cm^3 soil (Table 1). There was no difference in yield between PST (0.50 or 1 kg a.i. of aldicarb/ha) and VRT (0.84 kg a.i. aldicarb/ha) (Table 3). Woollyleaf bursage was negatively correlated ($P = 0.001$) with yield, but since the plots were harvested in a series of short (15.4-m) lengths, it was possible to eliminate the areas where the weeds were present. Yield did not differ between aldicarb treatments regardless of whether or not the weedy areas were eliminated.

Discussion

There was no consistent advantage in variable-rate application of aldicarb over the producer standard rate. The number of fields in which VRT increased yield or decreased nematicide usage was equal to the number of fields in which VRT did not increase yield and resulted in an increase in nematicide usage. The fields with the best response to variable-rate application were those where the producer rate of aldicarb was considered either too high (field 1) or too low (field 2) for the average root-knot nematode density. In fields 3, 7, and 8, where the producer rate of aldicarb was considered too low for the average root-knot nematode density, there was no response to the higher rate of aldicarb used in VRT.

The benefits of nematicide application for root-knot nematode control in cotton have been demonstrated (Jorgenson, 1979; Thomas and Smith, 1993). However, the ef-

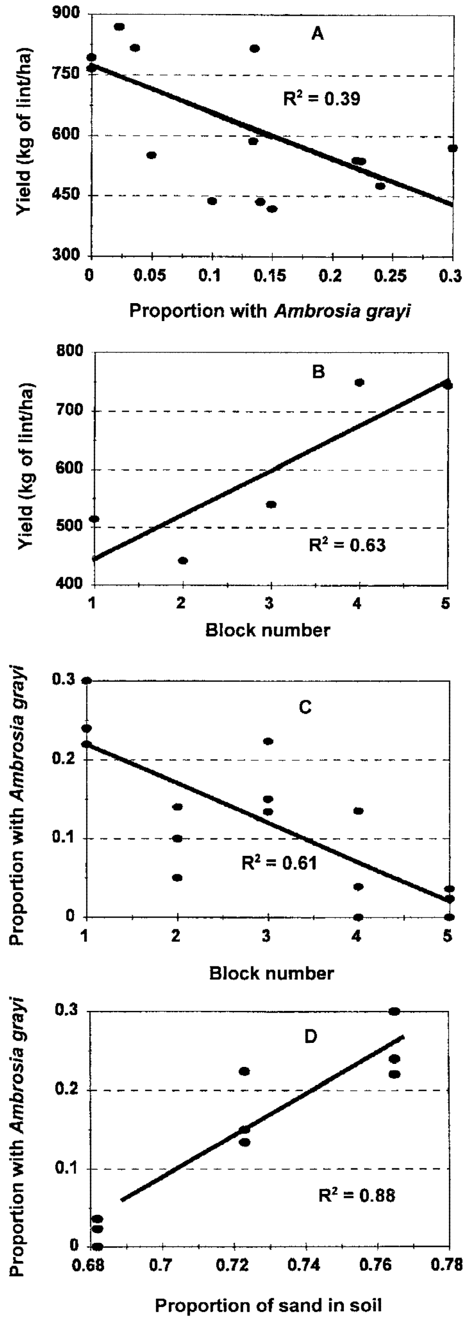

FIG. 2. Impact of woollyleaf bursage (*Ambrosia grayi*) on cotton yield (kg of lint/ha) at field 7 in 1998. A) Relationship between proportion of each plot with woollyleaf bursage (WB) and yield (yield = 774 − 1158 × WB. B) Relationship between block number and yield, where yield = 367 + 77 × Block number. C) Relationship between block number and proportion of each plot with woollyleaf bursage (WB), where WB = 0.27 − 0.05 × Block number. D) Relationship between proportion of sand content and proportion of plot with woollyleaf bursage (WB), where WB = −1.87 + 2.79 × sand content.

fects of nematicide application over a large area, where the rate was permitted to vary as a function of estimated nematode density, had not been previously demonstrated. The advantage of variable-rate application of nematicide over one constant rate of nematicide, with no information on nematode population density, was not consistently apparent in these tests.

There are a number of factors that can impact the effectiveness of aldicarb on plant growth and yield. The nematode species and population density are two critical factors; however, other plant stresses and the activation of aldicarb in the soil also may be important. Water stress may increase root-knot nematode damage on plant growth and yield (Wheeler et al., 1991). Variation in the concentration of phenamiphos in soil has been correlated with quantity of water received in field plots (Johnson et al., 1981). Field 8 received minimal irrigation at the beginning of the season (B. Baugh, unpubl.) It is not known if lack of water impacted the efficacy of aldicarb, but aldicarb is dispersed in the soil by mass transfer of water in the direction of water movement (Hough et al., 1975). Irrigation for the first 3 to 4 weeks after planting in field 8 may have been insufficient to effectively activate and redistribute the furrow-applied aldicarb. Aldicarb had not been applied to field 8 previous to 1998, so microbial degradation of aldicarb (Jones and Norris, 1998) was probably not a factor in the apparent lack of efficacy.

Little is known about interactions between weeds and cotton growth in root-knot nematode-infested fields. Chile (*Capsicum annuum*) grown in the presence of *M. incognita* and yellow nutsedge (*Cyperus esculentus*) had 22% greater shoot weights than chile grown in the absence of *M. incognita,* and shoot weights were similar to chile grown in the absence of weeds and nematodes (Thomas et al., 1997). In field 3/7, which was heavily infested with perennial weeds (woollyleaf bursage and Texas blueweed) and *M. incognita,* an increased rate of aldicarb was not associated with increased yield. The key to selecting fields where variable-rate application of aldicarb will be most effective may lie in identifying the factors most limiting to plant growth and a better understanding of interactions between root-knot nematode and weed or other crop stresses.

Year-to-year variation in nematicide studies is common (Johnson et al., 1998). Variability in nematode population densities, the producer choice of aldicarb rate, and the presence of weeds appeared to be more important than weather-related differences. In 1996, both tests indicated a benefit of VRT over PST, but the producers used inappropriate rates of aldicarb for the densities of root-knot nematode present. In 1997, there were all possible combinations (VRT better than, equal to, or worse than PST); however, each test can be explained in terms of nematode variability or weed pressure. The difference between VRT being better than or equal to PRT (field 4 vs. field 5) was probably related to nematode variability and aldicarb rate. The PST rate of aldicarb (0.50 kg/ha) used in field 5 was probably appropriate for 80% of the locations sampled (where root-knot nematode density was <1,000 eggs + J2/500 cm^3 soil) and too low for 20% of the locations (where root-knot nematode density was ≥1,000 eggs + J2/500 cm^2 soil). At field 4, the PST rate of aldicarb (0.83 kg/ha) was probably appropriate for 30–35% of the test area (where root-knot nematode density was ≥1,000 eggs + J2/500 cm^3 soil) and higher than necessary for the remainder (root-knot nematode density <1,000 eggs + J2/500 cm^3 soil). Thus, VRT was beneficial at field 4 but did not differ from PST in field 5. In 1998 there were two combinations where VRT was worse than PST (field 7 and 8), but both were in fields that had been chosen specifically with weed problems. This was done to demonstrate that the results from the weed-infested field in 1997 were consistent in other years, although weeds alone do not explain the results found with field 8. Weather may impact the year-to-year response of nematicides, but there was no clear weather-related response in this study.

Accurately and inexpensively identifying the locations of high or low densities of root-knot nematode within fields is a major impediment to variable-rate application of aldicarb. Fall sampling is considered more reliable than spring sampling for root-knot nematode density (Goodell, 1993), although spring sampling provided adequate results, particularly in 1996. In this study the cost of sampling and nematode analysis was not included in the comparison of the success of VRT over PST. In most fields, unless there are dramatic soil texture changes, such as occurred in field 6 where the sand content abruptly dropped from 75–89% down to 49–59%, subtle soil texture changes alone probably will not be accurate indicators of root-knot nematode population density.

Action and dosage thresholds for aldicarb application were arbitrarily defined at the beginning of this project. A damage threshold of 50 to 100 eggs/500 cm^3 soil for preplant density of *M. incognita* on cotton was defined by Starr et al. (1989). No precise relationship between root-knot nematode density and rate of aldicarb has been defined, although the labeled nematicide rate is 0.58 to 1.16 kg a.i./ha, applied in-furrow at planting (Rhône-Poulenc, 1994). Additional research defining the nematode density-dosage relationship would be beneficial. However, it is clear from this study that environmental or other biological factors may substantially impact nematode density-dosage relationships.

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