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Management of Root-knot Nematodes by Phenamiphos Applied through an Irrigation Simulator with Various Amounts of Water

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Abstract: Phenamiphos (6.7 kg a.i./ha) was applied via an irrigation simulator to squash at planting (AP) and 2 weeks after planting (PP), and to corn AP and 1 week PP to manage root-knot nematodes (*Meloidogyne incognita*). The nematicide was applied with 0.25, 0.64, 1.27, and 1.91 cm surface water/ha to a Lakeland sand in which the soil moisture was at or near field capacity. Based on efficacy and crop response, no additional benefits resulted when phenamiphos was applied in volumes of water greater than 0.25 cm/ha. The cost of applying each 0.25 cm of water over a hectare is approximately $1.08, or a 92% reduction in nematicide application cost over conventional methods ($13.50/ha). Low root-gall indices and high yields from squash and corn indicate more effective nematode management when phenamiphos was applied AP rather than PP. Results from this method of applying phenamiphos suggest that certain nematicides could be used as salvage alternatives when nematodes are detected in crops soon after planting. For multiple-pest management, nematicides, other compatible biocides, and fertilizers could be applied simultaneously with sprinkler irrigation.
Key words: Chemical control, *Criconemella ornata*, ring nematode, *Cucurbita pepo*, squash, *Meloidogyne incognita*, root-knot nematode, chemigation, nematicide, pest management, phenamiphos, *Zea mays*, corn.

Approximately 2.2 million ha of land are under irrigation in North Carolina, South Carolina, Georgia, Alabama, and Florida. The potential area involved in multiple-cropping sequences under irrigation could soon exceed 800 thousand ha in the southeastern Coastal Plain (10). Application of agrochemicals through irrigation water (chemigation) has been under investigation for several years. New irrigation technology has proved that irrigation is an important component in crop production (1,10) and pest management (2,3,5–9,12,13). Phenamiphos (6.7 kg a.i./ha) ap-

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TABLE 1. Number of *Meloidogyne incognita* second-stage juveniles per 150 cm^3 soil on squash as influenced by phenamiphos (6.7 kg a.i./ha) applied via irrigation simulator with different amounts of water.

		Days after planting									
	Water	0		7		14		21		88	
Treatment	(cm)	AP*	PP†	AP	PP	AP	PP	AP	PP	AP	PP
Control	0.64	419 a	53 b	43	80	20	20	35	10	6 b	59 a
Phenamiphos	0.25	273 a	20 b	58	35	8	55	13	10	6 b	124 a
Phenamiphos	0.64	418 a	13 b	45	4	10	16	23	10	11 b	24 a
Phenamiphos	1.27	300 a	4 b	83	4	3	13	3	18	6 b	89 a
Phenamiphos	1.91	480 a	10 b	75	9	3	14	13	23	5 b	100 a

Means followed by different letters in rows are significantly ($P = 0.05$) different according to Waller-Duncan's multiple-range test.
* AP = phenamiphos applied immediately after planting.
† PP = phenamiphos applied 2 weeks after planting.

plied in 123 kiloliters and 178 kiloliters water/ha at planting gave desired results (5–7). Our objectives were, in response to producers' questions, to determine the timing of nematicide application through irrigation systems and amounts of water needed to improve crop production.

MATERIALS AND METHODS

Plots were established in April 1981 on Lakeland sand (93.5% sand, 2.9% silt, 3.6% clay, pH 6.0–6.7) infested with root-knot nematodes *Meloidogyne incognita* (Kofoid & White) Chitwood race 1 and ring nematodes *Criconemella ornata* (Raski) de Grisse & Loof. Each plot contained three beds, 1.8 × 12.2 m each with two rows 0.9 m apart. The experimental design was split-plot with time of nematicide application as whole plots and amount of water as subplots. Treatments were replicated four times. All plots were irrigated with ca. 127 kiloliters water/ha (0.5 acre-inch) to stabilize and equalize soil moisture among plots. Treatments were applied 1 day after planting (AP) squash (*Cucurbita pepo* L. 'Dixie Hybrid') on 16 April and 2 weeks after planting (PP). Phenamiphos (6.7 kg a.i./ha) was applied through an irrigation simulator (11) with 0.25, 0.64, 1.27, or 1.91 cm water (ca. 0.1, 0.25, 0.5, or 0.75 acre-inch, respectively). Nontreated plots irrigated with 0.64 cm water served as controls. Fertilizer was applied at planting with ground applicators. Insecticides and fungicides were applied as needed with a ground sprayer.

Twenty soil cores (2.5 × 15 cm) for nematode assay were collected from the center 6 cm of the two outside beds 0, 7, 14, 21, and 88 days after planting. A 150-cm^3 soil aliquot was processed by the centrifugal-flotation method to separate nematodes from the soil (4). Roots of 10

TABLE 2. Root-gall indices and yield of squash as influenced by phenamiphos (6.7 kg a.i./ha) applied via irrigation simulator with different amounts of water.

		Days after planting				Total marketable yield	
	Water	40		88		(kg/ha)	
Treatment	(cm)	AP*	PP†	AP	PP	AP	PP
Control	0.64	4.9 a	4.8 a	5.0 a	5.0 a	1,616 c	874 b
Phenamiphos	0.25	1.3 b	3.5 a	2.9 c	4.9 a	7,938 a	5,062 a
Phenamiphos	0.64	1.4 b	4.2 a	3.5 b	4.8 a	7,044 ab	4,655 a
Phenamiphos	1.27	1.5 b	4.5 a	2.9 c	4.8 a	5,624 bc	5,590 a
Phenamiphos	1.91	1.3 b	4.6 a	3.1 bc	4.9 a	6,871 ab	6,088 a

Means followed by the same letter in columns or underscored by contiguous lines in rows are not significantly ($P = 0.05$) different according to Waller-Duncan's multiple-range test.
Scale: 1 = no galls, 2 = 1–25%, 3 = 26–50%, 4 = 51–75%, and 5 = 76–100% roots galled.
* AP = phenamiphos applied immediately after planting.
† PP = phenamiphos applied 2 weeks after planting.

plants from each of the two outside beds were examined for galls caused by *M. incognita* 40 and 88 days after planting. The center bed (two rows) was reserved for yield.

Squash was harvested 10 times at 3-day intervals from 1 June to 13 July, and the total weight of marketable fruit was recorded.

A similar test was established on corn (*Zea mays* L. 'Pioneer X 304C') following squash. Corn was planted on 28 July, AP nematicide treatments were applied the following day, and PP treatments were applied 1 week after planting. Soil samples were collected and assayed for nematodes as described for the squash test 0, 28, 55, 85, 114, 142, and 164 days after planting. Roots of 10 plants from each of the two outside beds were examined for galls caused by *M. incognita* 45 and 142 days after planting. Corn was hand harvested on 8 January and dried. Ear length and diameter, fill length, and yield (grain) per hectare were recorded.

Results and Discussion

Numbers of *C. ornata* at all sampling dates were fewer than 50/150 cm^3 soil and erratic in plots of squash on all sampling dates (data not included).

Pretreatment soil population densities of *M. incognita* second-stage juveniles (J2) on squash were greater in AP plots than PP plots, but numbers of *M. incognita* were greater in PP plots than AP plots 88 days after planting (Table 1). Numbers of *M. incognita* J2 in soil were not different among treatments on any sampling date.

Root-gall indices of squash 40 and 88 days after planting were lower in all AP-treated plots than in PP plots (Table 2). The indices were lower in AP plots than in the nontreated controls on both sampling dates but were not affected by treatments in the PP plots. Correlation coefficients indicated an inverse relationship between root-gall indices and yield 40 ($r = -0.55^{**}$) and 88 ($r = -0.51^{**}$) days after planting.

Total yield of squash was greater in both AP and PP plots than in nontreated controls (Table 2). In plots that received phenamiphos in 0.25 or 0.64 cm of water, yields were greater from AP than from PP plots. Yields from plants in AP vs. PP plots treated with larger amounts of water were not different. These results suggest that the solubility of phenamiphos (400 ppm) was exceeded, since there are only 53 ppm in the 1.27 cm water/ha. Therefore the nematicide probably traveled with the water to depths below the nematodes, or the dilution was not very effective in the shallow-rooted squash.

Pretreatment (day 0) soil population densities of *C. ornata* (Table 3) and *M. incognita* J2 (Table 4) on corn were not different among plots. Numbers of *C. ornata* in nontreated plots increased rapidly on corn to 660/150 cm^3 soil 85 days after planting and remained at high levels thereafter. Numbers of *C. ornata* at 28 days after planting and *M. incognita* J2 at 55 days in treated soil were lower than those in nontreated plots, not different among nematicide–water treatments, and not different AP vs. PP on most sampling dates. Correlation coefficients for numbers of *M. incognita* J2 in soil and root-gall indices of corn ranged from $r = 0.48^{**}$ to $r = 0.81^{**}$.

Root-galls caused by *M. incognita* on corn were fewer in AP plots than in PP plots and fewer in treated plots than in nontreated controls 45 days after planting, but not different among nematicide–water treated AP plots (Table 4). The trend was similar for root-gall indices in PP plots, except more galls occurred on plants in plots treated with nematicide–water (0.25 cm) than in other treated plots. Root-gall indices recorded 142 days after planting were lower in AP nontreated controls, nematicide–water (1.27 cm), and nematicide–water (1.91 cm) than in similar PP plots. The indices in treated AP and PP plots were lower than those in nontreated controls. Correlation coefficients indicated a negative relationship between root-gall indices and ear length ($r = -0.59^{**}$ to -0.61^{**}), ear diameter ($r = -0.58^{**}$ to -0.67^{**}), and fill length ($r = -0.66^{**}$ to -0.68^{**}).

Ear length, ear diameter, and fill length were not affected by time of nematicide application (AP vs. PP), or the amount of water used in the applications, but were larger from plants in treated plots than nontreated controls (Table 5). Grain yield from plants in treated AP plots was greater than from PP plots. The greatest yield from AP and PP treatments came from plants

TABLE 3. Numbers of *Criconemella ornata* per 150 cm^3 soil on corn as influenced by phenamiphos (6.7 kg a.i./ha) applied via irrigation simulator with different amounts of water.

		Days after planting													
	Water	0		28		55		85		114		142		164	
Treatment	(cm)	AP*	PP†	AP	PP	AP	PP	AP	PP	AP	PP	AP	PP	AP	PP
Control	0.64	41 a	98 a	108 a	78 a	193 a	136 a	660 a	660 a	533 a	496 a	783 a	550 a	805 a	538 a
Phenamiphos	1.25	11 a	20 a	23 b	3 b	0 b	0 b	3 b	0 b	9 b	3 b	9 b	4 b	14 b	0 b
Phenamiphos	0.64	18 a	8 a	25 b	10 b	3 b	3 b	3 b	0 b	4 b	0 b	9 b	3 b	1 b	0 b
Phenamiphos	1.27	19 a	10 a	13 b	13 b	20 b	14 b	5 b	8 b	5 b	13 b	9 b	14 b	18 b	8 b
Phenamiphos	1.91	5 a	18 a	18 b	33 b	5 b	5 b	3 b	0 b	3 b	6 b	0 b	4 b	0 b	4 b

Means followed by the same letter in columns are not significantly ($P = 0.05$) different according to Waller-Duncan's multiple-range test.
* AP = phenamiphos applied immediately after planting.
† PP = phenamiphos applied 1 week after planting.

TABLE 4. Numbers of *Meloidogyne incognita* second-stage juveniles per 150 cm^3 soil and root-gall indices of corn as influenced by phenamiphos (6.7 kg a.i./ha) applied via irrigation simulator with different amounts of water.

		Days after planting																	
		Number juveniles/150 cm^3 soil														Root-gall index			
	Water	0		28		55		85		114		142		164		45		142	
Treatment	(cm)	AP*	PP†	AP	PP	AP	PP	AP	PP	AP	PP	AP	PP	AP	PP	AP	PP	AP	PP
Control	0.64	69 a	105 a	13 a	20 a	58 a	114 a	583 a	325 a	649 a	525 a	1,168 a	1,013 a	1,040 a	708 a	2.00 a	2.38 a	2.15 a	2.65 a
Phenamiphos	0.25	58 a	58 a	28 a	28 a	0 b	21 b	5 b	35 b	4 b	13 b	68 b	53 b	25 b	204 b	1.05 b	1.70 b	1.13 b	1.18 d
Phenamiphos	0.64	184 a	68 a	15 a	38 a	3 b	19 b	0 b	5 b	5 b	9 b	3 b	68 b	3 b	38 d	1.00 b	1.48 c	1.00 b	1.13 d
Phenamiphos	1.27	53 a	110 a	28 a	38 a	0 b	56 b	3 b	40 b	4 b	93 b	8 b	115 b	3 b	615 a	1.00 b	1.43 c	1.13 b	1.60 b
Phenamiphos	1.91	64 a	150 a	58 a	33 a	0 b	64 b	8 b	63 b	0 b	21 b	6 b	81 b	1 b	85 c	1.00 b	1.55 c	1.03 b	1.28 c

Means followed by the same letter in columns or underscored by contiguous line in rows are not significantly ($P = 0.05$) different according to Waller-Duncan's multiple-range test.
* AP = phenamiphos applied immediately after planting.
† PP = phenamiphos applied 1 week after planting.

TABLE 5. Effect of phenamiphos (6.7 kg a.i./ha) applied via irrigation simulator with different amounts of water on ear length, ear diameter, fill length, and yield of corn.

Treatment	Water (cm)	Ear length (cm) AP*	Ear length (cm) PP†	Ear diameter (cm) AP	Ear diameter (cm) PP	Fill length (cm) AP	Fill length (cm) PP	Yield grain (kg/ha) AP	Yield grain (kg/ha) PP
Control	0.64	16.1 b	16.5 b	4.0 b	4.2 b	12.1 b	12.2 b	1,182 c	1,081 c
Phenamiphos	0.25	19.6 a	19.8 a	4.8 a	4.8 a	15.9 a	15.9 a	3,323 a	3,033 a
Phenamiphos	0.64	19.8 a	18.8 a	4.9 a	4.9 a	16.3 a	14.8 a	3,006 a	2,520 b
Phenamiphos	1.27	18.8 a	19.1 a	4.8 a	4.6 a	15.2 a	15.2 a	2,696 b	2,333 b
Phenamiphos	1.91	19.5 a	19.4 a	4.9 a	4.8 a	15.8 a	15.6 a	3,221 a	2,790 ab

Means followed by the same letter in columns or underscored by contiguous line in rows are not significantly ($P = 0.05$) different according to Waller-Duncan's multiple-range test.

* AP = phenamiphos applied immediately after planting.

† PP = phenamiphos applied 1 week after planting.

in plots treated with phenamiphos in 0.25 cm water. Ear length, ear diameter, and fill length were inversely related to numbers of *C. ornata* and *M. incognita* J2 in the soil and root-gall indices and positively related to grain yield (Table 6). Grain yield was inversely related to numbers of *C. ornata* and *M. incognita* J2 in the soil and root-gall indices. These results indicate that both *C. ornata* and *M. incognita* negatively influenced yield and quality of corn.

Three advantages in applying nematicides with irrigation water are 1) ability to control the depth of soil penetration with the volume of water, 2) lower cost compared with conventional applicators, and 3) marked reduction in hazards to the applicator. Our results indicated that phenamiphos can be safely applied through a sprinkler irrigation system with 0.25 cm/ha water for nematode management on squash and corn on deep sandy soil when soil moisture is at or near field capacity. No additional benefits resulted, based on efficacy and crop response, when phenamiphos was applied in volumes of water greater than 0.25 cm/ha. The cost of applying each 0.25 cm of water over a hectare is approximately $1.08 (10), a 92% reduction in nematicide application cost over conventional methods ($13.50/ha). Application of phenamiphos in irrigation water provides a relatively safe method for the applicator in that it is very difficult to receive a toxic dose. For example, the LD_{50} oral for female rats is 11 and dermal 282 mg/kg (8), or 749 and 19,176 mg for a 68 kg man, or the equivalent of 2.8 and 64.4 liters of the 0.25 cm/ha water solution, respectively, as compared with conventional applications of 187 liters/ha or 21 ml oral and 53 ml dermal.

Nematode population densities, root-gall indices, ear length, ear diameter, fill length, and yield were not significantly different among the phenamiphos–water treatments on most sampling dates. These results indicate that these parameters responded similarly when the nematicide was applied in different amounts of water.

Nematicides are used primarily to decrease nematode population densities in soil before planting annual crops. The low root-gall indices and high yields from squash and corn indicated more effective management of nematodes when phenamiphos was applied AP rather than PP. Since root-gall indices were lower and yields of both

TABLE 6. Correlation coefficients (*r*) for variables of corn, nematodes, and root-gall indices.*

Variable	Number/150 cm³ soil: *Criconemella ornata*	Number/150 cm³ soil: *Meloidogyne incognita* J2	Root-gall indices	Grain yield
Ear length	−0.63 to −0.76	−0.42 to −0.49	−0.59 to −0.61	0.80
Ear diameter	−0.69 to −0.80	−0.45 to −0.57	−0.58 to −0.67	0.84
Fill length	−0.67 to −0.74	−0.41 to −0.53	−0.66 to −0.68	0.86
Grain yield	−0.58 to −0.74	−0.55 to −0.75	−0.74 to −0.75	

* All correlation coefficients were significant ($P = 0.01$).

crops were higher from PP treated plots than from nontreated plots, and no symptoms of phytotoxicity were observed, the results indicated that the nematicide application technology could be used as a salvage alternative when nematodes are detected in crops after planting.

As new irrigation technology is developed, it seems feasible that nematicides, other compatible biocides, and fertilizers could be applied simultaneously via sprinkler irrigation for multiple-pest management in crop production. More research on other crops, nematodes, soil types, and climatic conditions is needed to determine the soil–water–nematicide relationships when nematicides are applied via sprinkler irrigation systems.

Literature Cited

1. Bryan, B. B., and E. L. Thomas, Jr. 1958. Distribution of fertilizer materials applied through sprinkler irrigation systems. Bulletin 598. University of Arkansas Agricultural Experiment Station, Fayetteville.
2. Chalfant, R. B., and J. R. Young. 1982. Chemigation or application of insecticides through an overhead sprinkler irrigation system to manage insects in testing vegetables and agronomic crops. Journal of Economic Entomology 75:237–241.
3. Dowler, C. C., W. A. Rohde, L. E. Fetzer, D. E. Scott, Jr., T. E. Sklany, and C. W. Swann. 1982. The effect of sprinkler irrigation on herbicide efficacy, distribution, and penetration in some Coastal Plain soils. College of Agriculture Research Bulletin 281. University of Georgia, Athens.
4. Jenkins, W. R. 1964. A rapid centrifugal-flotation technique for separating nematodes from soil. Plant Disease Reporter 48:692.
5. Johnson, A. W. 1978. Effects of nematicides applied through overhead irrigation on control of root-knot nematodes on tomato transplants. Plant Disease Reporter 62:48–51.
6. Johnson, A. W., W. A. Rohde, and W. C. Wright. 1982. Soil distribution of fenamiphos applied by overhead sprinkler irrigation to control *Meloidogyne incognita* on vegetables. Plant Disease 66:489–491.
7. Johnson, A. W., J. R. Young, and B. G. Mullinix. 1981. Applying nematicides through an overhead sprinkler irrigation system for control of nematodes. Journal of Nematology 13:154–159.
8. Mobay Chemical Corporation. 1976. Technical information on nemacur. Chemagro Agricultural Division, Kansas City, Missouri.
9. Sumner, D. R., S. C. Phatak, D. Smittle, A. W. Johnson, and N. C. Glaze. 1981. Control of cucumber foliage diseases, fruit rot, and nematodes by chemicals applied through overhead irrigation water. Plant Disease 65:401–404.
10. Threadgill, E. D. 1984. Chemigation via sprinkler irrigation: Current status and future development. ASAE Paper No. 84-2098, American Society of Agricultural Engineers, Knoxville, Tennessee (Abstr.).
11. Threadgill, E. D., and C. C. Dowler. 1984. Irrigation systems simulator for small plot research. Proceedings Annual Meeting American Society of Agronomists, Las Vegas, Nevada, 25–30 November. P. 46. (Abstr.).
12. Young, J. R., editor. 1981. Proceedings of the National Symposium on Chemigation. University of Georgia, Tifton.
13. Young, J. R., and D. R. Sumner, eds. 1982. Proceedings of the Second National Symposium on Chemigation. University of Georgia, Tifton.