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Effect of Simulated Rainfall on Efficacy and Leaching of Two Formulations of Fenamiphos[1]

A. W. JOHNSON,[2] R. D. WAUCHOPE,[2] AND D. R. SUMNER[3]

Abstract: Recoverable fenamiphos in the soil and residue in squash following different simulated rainfall treatments after nematicide application were determined in a 2-year study. Efficacy of fenamiphos also was evaluated. Fenamiphos treatments (3 SC and 15 G) were broadcast (6.7 kg a.i./ha) over plots and incorporated into the top 15 cm of soil immediately before planting 'Dixie Hybrid' squash. Simulated rainfall treatments of 0, 2.5, and 5.0 cm water were applied 1 day after fenamiphos application. Soil samples from 0- to 8-cm, 8- to 15-cm, and 15- to 30-cm soil depths were collected 1 day after the simulated rainfall applications and analyzed for fenamiphos, fenamiphos sulfoxide (FSO), and fenamiphos sulfone (FSO_2). Squash was analyzed for total fenamiphos residue. Greater concentrations of fenamiphos were present in the 0- to 8-cm soil layer following application of 15 G than 3 SC formulation. Simulated rainfall treatments did not alter fenamiphos concentrations in any soil layer (except for the 0- to 8-cm depth in 1992) or concentration of FSO and total fenamiphos residue in the 15- to 30-cm soil layer. Root-gall indices were greater from untreated than most fenamiphos-treated plots, but were not affected by formulations of fenamiphos or simulated rainfall treatments. Concentrations of total residue in squash ranged from 1 to 4 μg FSO_2/g.

Key words: Cucurbita melopepo, efficacy, fenamiphos, leaching, management, *Meloidogyne incognita,* nematicide, nematode, root-knot, root-knot nematode, squash.

Use of fenamiphos 3 SC and 15 G (an organophosphate nematicide-insecticide) to manage plant-parasitic nematodes on vegetable crops is expanding following the loss of registration for soil fumigants (8). In the soil, fenamiphos is rapidly oxidized to fenamiphos sulfoxide (FSO), which is slowly oxidized to fenamiphos sulfone (FSO_2) (15,16). FSO and FSO_2 have pesticidal activity and toxicity similar to that of fenamiphos (27), but FSO and FSO_2 are much more mobile (1,15,21) and persistent than fenamiphos (20) in soils. Degradation of fenamiphos varies with the history of soil exposure to the chemical (6,7, 19), soil type (9,10,23), tillage methods (16), and microorganisms (20). Fenamiphos residue in soil does not persist longer than 30 days under field conditions (10,16, 18).

If rainfall occurs shortly after fenamiphos application, nematicidal efficacy may be reduced because of enhanced movement of fenamiphos. Simulated rainfall (2.5 to 5.0 cm) 1 and 3 days after application of fenamiphos 15 G had little effect on fenamiphos efficacy, soil residues, or residues in squash fruit (11). However, total recoveries of fenamiphos from soil, even from plots without simulated rainfall, were only 40% to 70%. The objectives of this study were to determine the degradation, leaching, and efficacy of fenamiphos (15 G and 3 SC) in the soil using improved soil sampling procedures, and to determine fenamiphos residues in squash fruit, with and without simulated rainfall 24 hours after nematicide application.

MATERIALS AND METHODS

A field experiment was conducted to determine the effects of simulated rainfall treatments on recovery of fenamiphos from three soil depths and the efficacy of fenamiphos for controlling southern root-knot nematode (*Meloidogyne incognita*) (Kofoid and White) Chitwood) race 1 in squash (*Cucurbita pepo* var. *melopepo* (L.)

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[2] Supervisory Research Nematologist and Research Chemist, USDA ARS, Coastal Plain Station, Tifton, GA 31793-5401.

[3] Professor, Department of Plant Pathology, University of Georgia, Coastal Plain Station, Tifton, GA 31793-5401.

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E-mail: nemweeds@tifton.cpes.peachnet.edu.

Alef.). The experimental design was a randomized complete block replicated four times over 2 years. Treatments were all combinations of two formulations of fenamiphos (Nemacur 15 G and 3 SC, Miles Inc., Kansas City, MO) and three simulated rainfall treatments (0, 2.5, and 5.0 cm water) plus an untreated control. The experiment was established in May 1992 and repeated in 1993 on Tifton loamy sand (fine-loamy, siliceous, thermic Plinthic Paleudults; 85% sand, 10% silt, 5% clay; pH 6.0, 0.5% organic matter) infested with *M. incognita* race 1 (22). The soil was disc-harrowed, plowed 25 to 30 cm deep with a moldboard plow, and shaped into beds 1.8 m wide and 10 to 15 cm high. Fenamiphos was broadcast at 6.7 kg a.i./ha over plots and incorporated into the top 15-cm soil layer with a tractor-mounted rototiller. Immediately after application of fenamiphos, seeds of squash cv. Dixie Hybrid were planted 30 cm apart in rows 0.91 m apart and 3 m long.

Simulated rainfall treatments were applied using a rainfall simulator designed to deliver a raindrop energy and size distribution similar to natural, intense rain (17). The design uses two oscillating 80150 Tee Jet (Spraying Systems Co., Wheaton, IL) nozzles and was calibrated to deliver 5-acre-cm of water per hour. The simulated rainfall treatments were applied 1 day after fenamiphos application. Four rain gauges were placed 0.5 m inside the corners of each plot to measure the rainfall.

Soil sampling procedure: Four areas were sampled at random within each plot 24 hours after simulated rainfall applications. A U.S. Environmental Protection Agency-designed "wide-area sampler" (24) was driven into the soil and a core 25.4-cm-diam. × 8-cm-deep was collected. The sampler was then driven deeper and a second core was collected from the 8- to 15-cm soil depth. Then, a bulb planter was used to collect three 15-cm-diam. cores from the same hole at the 15- to 30-cm soil depth. The four samples from each of the three depths within each plot were composited, placed in plastic bags, and frozen at −20 °C until they could be analyzed for fenamiphos, FSO, and FSO_2. Fenamiphos was added to soil from control plots, frozen, and used for calibration and recovery standards when the samples were assayed.

On the same day that the soil samples were collected for fenamiphos analysis, known volumes of soil were taken from each depth in the same plots and weighed before and after oven-drying 24 hours at 105 °C to determine dry-soil bulk density ρ_b (g/cm^3) and gravimetric moisture content θ (g/g) (3,14).

Fenamiphos assay: Soil samples were thawed and 50 g moist soil was combined with 200 ml extracting solution (5:4:1 v/v/v methylene chloride:methanol:water) in an Erlenmeyer flask and shaken for 2 hours on a rotary shaker. This mixture was filtered into a flask and evaporated with a rotary evaporator until dry. Ten milliliters methanol was added to the flask and evaporated until dry. Finally, 2 ml acetonitrile was added to the flask and the contents passed through a syringe membrane filter into a high-performance liquid chromatograph vial. The detection limits were 0.008 ppm (μg/g) for fenamiphos and 0.002 ppm (μg/g) for FSO and FSO_2.

To compare fenamiphos, FSO, and FSO_2 concentrations found in soil samples to the application rate per unit area (6.7 kg/ha = 67 μg/cm^2), the mass m_i of each species i found per area of field surface (μg/cm^2), corrected to parent fenamiphos mass, was calculated for each soil layer by

$$m_i = C_i \cdot (M_{fen}/M_i) \cdot \rho_b \cdot (1 - \theta)^{-1} \cdot L$$

where C_i is the concentration (μg/g) of species i (fenamiphos, FSO, or FSO_2) found by analysis, M_i is the molecular weight of species i, M_{fen} is the molecular weight of fenamiphos, ρ_b is the dry soil bulk density of the soil layer (g/cm^3), θ is the moisture content of the soil layer (g/g), and L is the depth (cm) of the layer.

Plant stand counts were recorded 2, 3, 4, and 10 weeks after planting in 1992. Twenty soil cores (2.5-cm-diam. × 15-cm deep) were collected within the rows of each plot on 20 May, 17 June, and 29 July 1992 and 10 May, 15 June, and 20 July 1993. The cores were composited and thoroughly mixed. Plant-parasitic nematodes were assayed from a 150-cm^3 subsample using centrifugal flotation (5).

Squash was hand-harvested 16 times from 22 June through 29 July 1992 and 15 times from 14 June through 19 July 1993. Numbers of marketable fruits and culls were counted and weighed. During the first harvest, 34 days after planting each year, 10 squash fruits were arbitrarily selected from each treatment, packed in plastic bags, and stored in a freezer at −20 °C until analyzed for total fenamiphos residue (fenamiphos, FSO, and FSO_2) (26). For calibration and recovery standards, fenamiphos was added to fruit samples from untreated plots and stored under similar conditions.

Two plants per plot were uprooted 30 days after planting in 1992 and 36 days after planting in 1993, and roots were rated for severity of galling. All plants were uprooted after the final harvest each year and rated for severity of galling. The root-gall index was based on a 1- to 5-scale: 1 = 0%, 2 = 1% to 25%, 3 = 26% to 50%, 4 = 51% to 75%, and 5 = 76% to 100% roots galled.

Data were analyzed using analysis of variance (25). Means were separated using k-ratio *t*-test (k = 100) (28). Regression analysis was used to relate root-gall indices to nematode numbers and yield. Single-degree-of-freedom contrast of means was used to compare certain treatments.

Results and Discussion

No natural rainfall occurred during the first 10 days of the tests in 1992 and 1993. The coefficient of variation for the four rain gauges was 7% to 10% within and among plots for both simulated rainfall rates and both years. The mean measured simulated rainfall was 2.4 ± 0.2 cm and 4.8 ± 0.5 cm in 1992 and 2.7 ± 0.2 cm and 5.1 ± 0.2 cm in 1993 for the 2.5-cm and 5.0-cm rates, respectively.

Volumetric water content increased with soil depth and was similar for both simulated rainfall rates (Fig. 1) in both years. These results, which agree with those of a previous study (11), indicate that either simulated rainfall amount was sufficient to saturate the soil or the excess moisture had percolated through the soil in the 24 hours elapsed between simulated rainfall application and soil sampling. Moisture gains per unit area were 1.03 and 1.02 cm in 1992 and 1.43 and 1.48 cm in 1993 for the 2.5-cm and 5.0-cm simulated rainfall treatments, respectively. Thus, 20% to 56% of the applied moisture was recovered in the top 30 cm of soil, and the remaining moisture percolated through the soil or evaporated during the 24 hours between application and sampling. Approximately 66% of the moisture gain was in the 15- to 30-cm soil layer. The moisture levels found in all plots were similar to field-capacity (33 kPa) values for this soil (4).

The mean bulk density (g/cm^3) of soil at various depths was 1.13 (0 to 8 cm), 1.80 (8 to 15 cm), and 1.82 (15 to 30 cm) and was not different among the treatments. The data on bulk density of the soil in this study were similar to those previously reported (4,11).

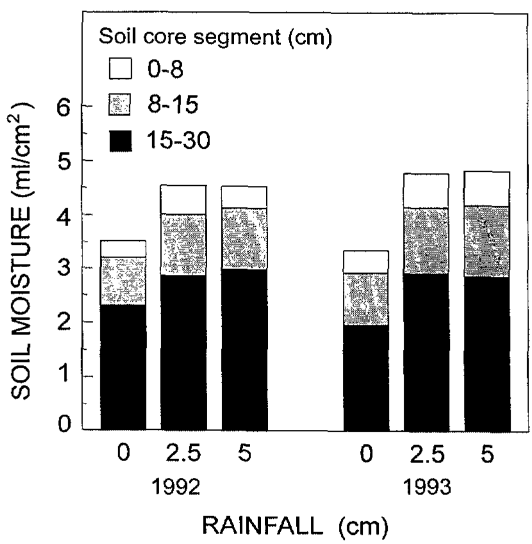

Fig. 1. Soil moisture in soil core segments between 0 and 30 cm as influenced by various amounts of rainfall.

In 1992, 84% of the fenamiphos, 94% of the FSO, and 98% of the total fenamiphos recovered from treated plots was found in the 0- to 15-cm soil layer. Even with simulated rainfall, only small amounts (≤ 0.329 ppm) of fenamiphos occurred in the 15- to 30-cm soil layer (Table 1, Fig. 2). Simulated rainfall treatments did not affect concentrations of fenamiphos in any soil depth except for the 0- to 8-cm depth in 1992, or concentrations of FSO or total fenamiphos residues in the 15- to 30-cm soil layer. Concentrations of FSO and total fenamiphos residues in the 0- to 8-cm soil layer were greater following 2.5 than 5.0 cm of simulated rainfall, and were greater in the 8- to 15-cm soil layer following 5.0 than 2.5 cm of simulated rainfall.

Greater concentrations of fenamiphos in the 0- to 8-cm soil layer occurred following application of 15 G than 3 SC formulation. However, concentrations of FSO and total fenamiphos residue in the 0- to 8-cm soil layer were greater following application of 15 G than 3 SC formulation. The concentrations of fenamiphos, FSO, and total fenamiphos residues in the 8- to 15-cm and 15- to 30-cm soil layers were not affected by formulations of fenamiphos.

In 1993, 99% to 100% of all fenamiphos, FSO, and total fenamiphos residues remained in the 0- to 15-cm soil layer in all plots (Table 2, Fig. 2). Only traces (≤ 0.015 ppm) of fenamiphos were found in the 15- to 30-cm soil layer. Similar results have been reported from studies in which no rainfall occurred after nematicide application (9–11,16). In Dothan and Fuquay soils, more than 90% of the fenamiphos recovered was from the 0- to 10-cm soil layer (18). Simulated rainfall treatments did not affect concentrations of fenamiphos, FSO, or total fenamiphos residues in any soil depths. The concentrations of fenamiphos and total fenamiphos residues at the 0- to 8-cm soil layer were greater from plots treated with the 15 G than the 3 SC formulation. Concentrations of FSO at the three soil depths were not affected by formulation of fenamiphos.

Concentrations of fenamiphos in the 0- to 8-cm soil layer were lower in plots treated with the 3 SC formulation followed by simulated rainfall treatments than plots with similar treatments but no rainfall. Simulated rainfall did not affect concentrations of fenamiphos, FSO, and total fenamiphos residues in 15 G-treated plots.

In both years, fenamiphos was not leached from the 0- to 8-cm soil layer, and less than 1 ppm FSO was detected in the 8- to 15-cm soil layer. The fenamiphos concentrations observed in these experiments were in the same order of magnitude as those reported by others (16). Dissipation of fenamiphos was similar to that previously reported (18).

Data in Fig. 3 show how the total mass of fenamiphos recovered from the 0- to 30-cm soil profile was distributed among the three fenamiphos compounds for the two formulations of fenamiphos. There was greater oxidation of the granular formulation of fenamiphos to the sulfoxide and less recovery of the SC formulation in 1993 than in 1992. Given the ease of oxidation of fenamiphos, the greater recovery of sulfoxide in 1993 may be an artifact due to some difference in procedure. We have no explanation for the apparent loss (or possibly low application rate) of the SC formulation in 1993.

In contrast to results of the 1990–1991 study (11), fenamiphos recoveries in this study were improved. Recoveries from soil samples fortified at 0.1 to 1.0 μg/g with technical fenamiphos were 95 ± 13%. Recoveries of total fenamiphos residues from soil samples to the 30-cm depth ranged from 51% to 114% of amount applied with an average recovery of 83% for both years and both formulations. We believe that the use of a larger field soil sample, cooler temperatures (average soil temperatures during the experiments were 26 and 25 °C in 1992 and 1993, respectively, and 28 and 29 °C in 1990 and 1991), and a shorter time period between nematicide treatment and soil sampling (2 days in 1992–1993; 4 days in 1990–1991) improved recoveries. This suggests that under warm and wet conditions, capillary movement of chemi-

TABLE 1. Concentrations (μg/g) of fenamiphos, fenamiphos sulfoxide, and total fenamiphos residues in the soil at various depths 1 day after application as influenced by simulated rainfall and nematicide formulation, 1992.

Treatment			Soil depth								
			Fenamiphos			Fenamiphos sulfoxide			Total fenamiphos residues		
Number	Simulated rainfall (cm)	Fenamiphos formulation	0–8 cm	8–15 cm	15–30 cm	0–8 cm	8–15 cm	15–30 cm	0–8 cm	8–15 cm	15–30 cm
1	2.5	3SC	1.19	0.20	0.030	3.81	1.03	0	4.99	1.23	0.030
2	5.0	3SC	0.91	0.12	0.167	3.51	1.28	0.259	4.42	1.52	0.427
3	2.5	15G	1.09	0	0.329	4.59	0.99	0	5.68	1.07	0.329
4	5.0	15G	1.09	0.34	0	3.80	1.50	0.174	4.88	1.91	0.174
5	0	3SC	0.98	0	0	5.04	0.74	0	6.02	0.74	0
6	0	15G	1.76	0.09	0	4.02	0.69	0	5.77	0.78	0
LSD ($P = 0.05$)			NS	0.24	NS	1.43	0.62	NS	1.31	0.74	NS
Single-degree-of-freedom contrast:											
1 + 3 vs. 2 + 4			NS[a]	NS	NS	**	*	NS	**	*	NS
1 + 2 vs. 3 + 4			NS	NS	NS	**	NS	NS	**	NS	NS
1 + 2 vs. 5			NS	NS	NS	NS	NS	NS	NS	NS	NS
3 + 4 vs. 6			NS	NS	NS	**	NS	NS	**	NS	NS
1 + 2 + 3 + 4 vs. 5 + 6			*	NS	NS	**	NS	NS	**	NS	NS

Data are means of four replicates.
[a] NS = nonsignificant ($P = 0.05$), * = $P = 0.05$, and ** = $P = 0.01$.

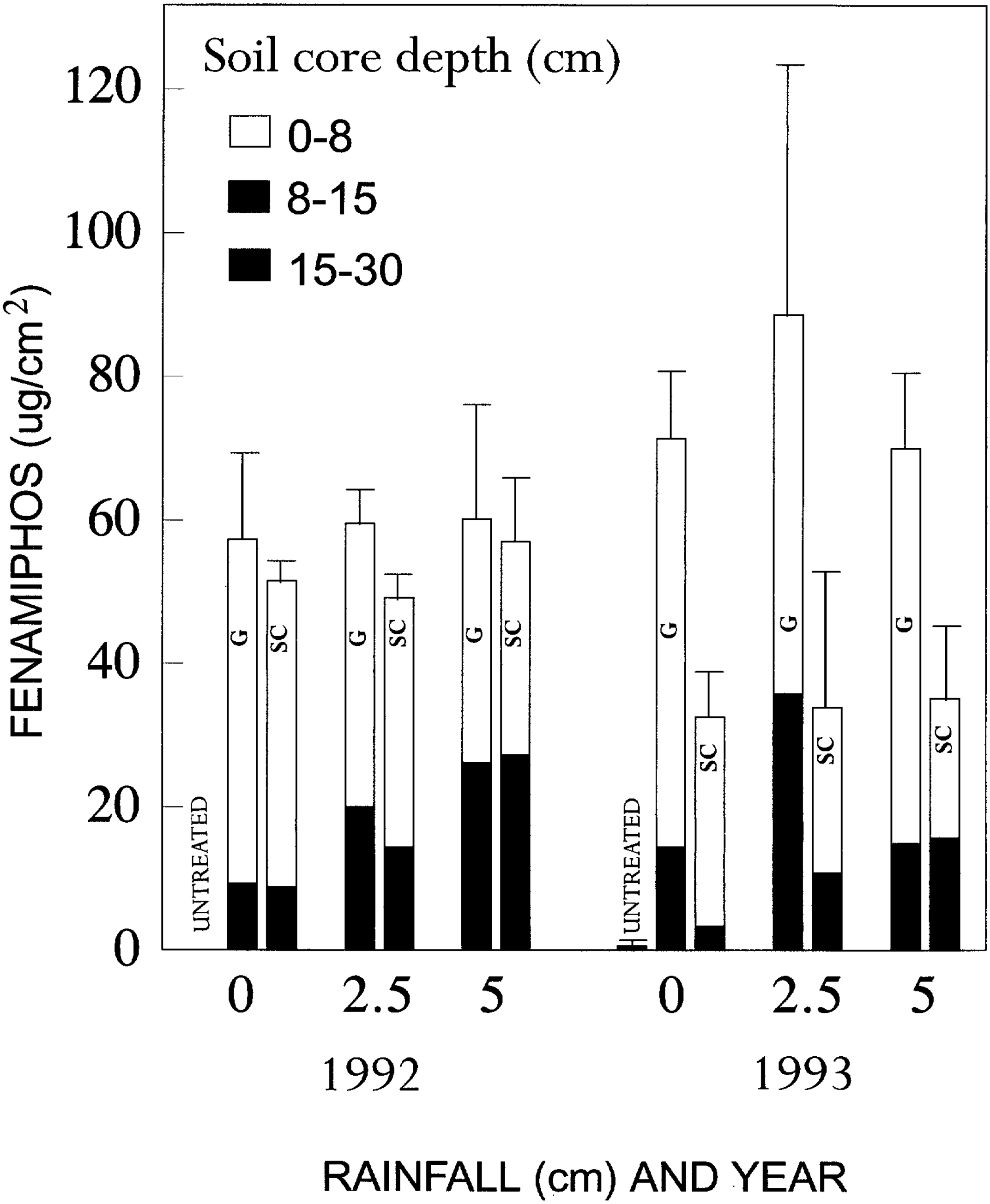

FIG. 2. Total fenamiphos residues found in soil (masses of oxides converted to equivalent parent fenamiphos masses), showing distribution of residues among the three soil sampling depths as affected by simulated rainfall and formulation: G = 15% granule; SC = spray concentrate. Application rate was 6.7 kg a.i./ha (67 $\mu g/cm^2$, as fenamiphos).

cals to the soil surface and subsequent volatilization may be an important loss pathway for fenamiphos, and that conditions favored greater losses in 1990–91.

Lee et al. (15) reported that the half-life of fenamiphos was only 2 days and the half-lives of fenamiphos oxidation products FSO and FSO_2 were 81 and 16 days, respectively. Fenamiphos did not leach from a sandy soil when applied at 9 kg

TABLE 2. Concentrations (μg/g) of fenamiphos, fenamiphos sulfoxide, and total fenamiphos residues in the soil at various depths 1 day after application as influenced by simulated rainfall and nematicide formulation, 1993.

Treatment			Soil depth								
			Fenamiphos			Fenamiphos sulfoxide			Total fenamiphos residues		
Number	Simulated rainfall (cm)	Fenamiphos formulation	0–8 cm	8–15 cm	15–30 cm	0–8 cm	8–15 cm	15–30 cm	0–8 cm	8–15 cm	15–30 cm
1	2.5	3SC	2.34	0.57	0.004	0.88	0.32	0	3.23	0.89	0.004
2	5.0	3SC	2.08	1.10	0	0.64	0.18	0	2.72	1.30	0
3	2.5	15G	6.04	2.74	0.009	1.30	0.19	0	7.34	2.94	0.009
4	5.0	15G	6.86	1.14	0.005	0.77	0.08	0	7.63	1.22	0.005
5	0	3SC	3.61	0.23	0.015	0.35	0	0	3.97	0.24	0.015
6	0	15G	6.98	1.16	0	0.74	0	0	7.72	1.16	0
LSD (P = 0.05)			1.79	2.15	NS	NS	NS	NS	1.80	2.34	NS
Single-degree-of-freedom contrast:											
1 + 3 vs. 2 + 4			NS[a]	NS	NS	NS	NS	NS	NS	NS	NS
1 + 2 vs. 3 + 4			**	NS	NS	NS	NS	NS	**	NS	NS
1 + 2 vs. 5			*	NS	NS	NS	NS	NS	NS	NS	NS
3 + 4 vs. 6			NS	NS	NS	NS	NS	NS	NS	NS	NS
1 + 2 + 3 + 4 vs. 5 + 6			NS	NS	NS	NS	NS	NS	NS	NS	NS

Data are means of four replicates.
[a] NS = nonsignificant (P = 0.05), * = P = 0.05, and ** = P = 0.01.

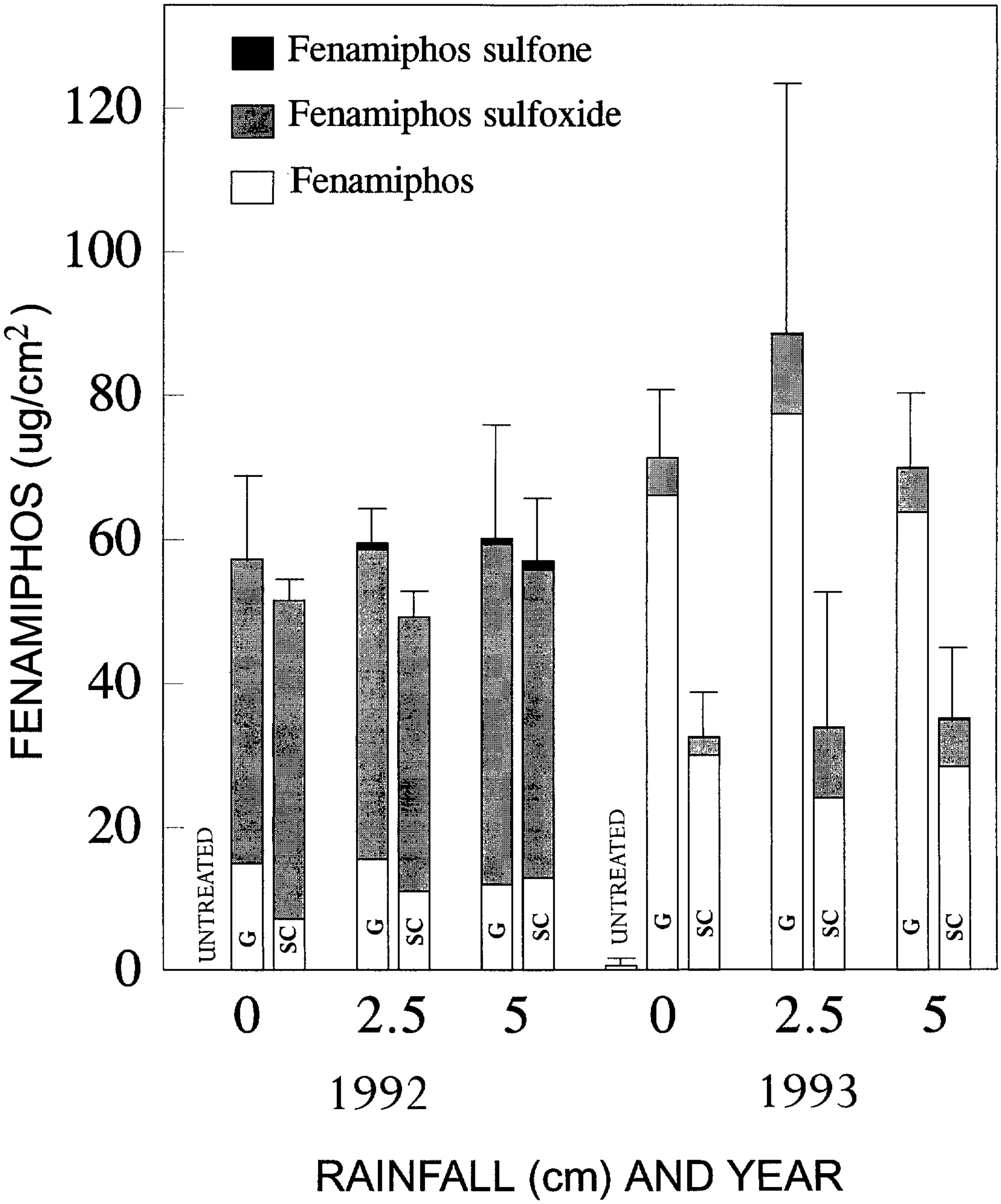

FIG. 3. Total fenamiphos residues found in soil (masses of oxides converted to equivalent parent fenamiphos masses), from 0- to 30-cm depth, showing distribution among fenamiphos species as affected by simulated rainfall and formulation: G = 15% granule; SC = spray concentrate. Application rate was 6.7 kg a.i./ha (67 $\mu g/cm^2$, as fenamiphos).

a.i./ha (9). However, rapid movement of fenamiphos, FSO, and FSO_2 occurred in the 8- to 15-cm soil layer when two to four times (18 kg a.i./ha) the recommended dosage for nematode control was applied in irrigation water (10).

The numbers of *M. incognita* second-stage juveniles (J2) in the soil were low and erratic on each sampling date (data not included) and were not affected by treatments, but were positively (P = 0.05) correlated (r = 0.43 to r = 0.77 in 1992 and

r = 0.30 to r = 0.69 in 1993) with root-gall indices. In both years, root-gall indices were larger from the untreated than most fenamiphos-treated plots, but were not affected by fenamiphos formulation or simulated rainfall treatments (Table 3).

Yield, expressed as number of fruit and metric tons per hectare, was not affected by fenamiphos treatments, fenamiphos formulations, or simulated rainfall treatments in 1992 (Table 3). In 1993, yield was greater from most fenamiphos-treated plots than untreated plots, but was not affected by fenamiphos formulation or simulated rainfall treatments. Generally, a yield increase of squash results from fenamiphos treatment when root-gall indices are 2.00 or greater in untreated plots and near 1.00 in treated plots approximately 30 days after planting (12,13). The lower root-gall indices and yield response in 1992 than 1993 was probably related to lower population densities of *M. incognita* in the soil.

Concentrations of FSO_2 in squash fruit, 34 days after planting and fenamiphos application, were below 0.05 ppm in 1992 and ranged from 0.00120 to 0.00448 ppm in 1993 (data not included). These concentrations of fenamiphos residue in squash fruit are far below the tolerance established for fenamiphos on other vegetable crops: 0.10 ppm, cabbage and eggplant; 0.30 ppm, okra; and 0.60 ppm, non-bell pepper (2).

Although climate and soil type may affect fenamiphos leaching losses, this experiment was done under conditions conducive to such losses—a sandy soil with 2.5 and 5.0 cm simulated rainfall applied 24 hours after nematicide application. Thus, these data suggest that fenamiphos retreatment following rainfall is likely to be unnecessary if at least 1 day elapses between nematicide application and rainfall.

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TABLE 3. Root-gall indices and yield of squash as influenced by simulated rainfall and fenamiphos formulation.

Treatment		Root-gall index[a]		Yield	
Simulated rainfall (cm)	Fenamiphos formulation	June	July	Number/ha (× 1.000)	mt/ha
				1992	
2.5	3 SC	1.50	2.58	166.8	75.9
5.0	3 SC	1.13	1.83	191.0	88.2
2.5	15 G	1.25	2.23	197.3	80.4
5.0	15 G	1.00	1.53	190.1	85.0
0	3 SC	1.38	2.75	203.5	90.8
0	15 G	1.13	2.03	194.6	87.8
0	Control	1.88	2.83	181.6	76.5
LSD (P = 0.05)		NS	NS	NS	NS
				1993	
2.5	3 SC	1.63	3.83	476.1	52.1
5.0	3 SC	1.13	3.03	472.1	53.7
2.5	15 G	1.50	3.70	526.8	57.2
5.0	15 G	2.00	3.55	527.2	56.5
0	3 SC	1.63	3.05	538.4	61.2
0	15 G	1.75	3.98	544.7	60.0
0	Control	2.13	3.18	417.8	43.1
LSD (P = 0.05)		NS	NS	95.2	10.5

Data are means of four replicates.

[a] Root-gall index scale 1 to 5: 1 = no galls, 2 = 1% to 25%, 3 = 26% to 50%, 4 = 51% to 75% and 5 = 76% to 100% roots galled.

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