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

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Abstract: There is increasing concern in the United States about the pesticide movement in soil, groundwater contamination, and pesticide residue in food. The objective of this study was to determine the efficacy, degradation, and movement of fenamiphos (Nemacur 15G) in the soil and residues in squash fruit as influenced by four simulated rainfall treatments (2.5 or 5.0 cm each applied 1 or 3 days after nematicide application) under field conditions. In 1990, concentrations of fenamiphos were greater in the top 15 cm of soil in plots with no rainfall than in those treated with rainfall. Eighty to 95% of the fenamiphos recovered from treated plots was found in the 0–15-cm soil layer. The concentration of fenamiphos recovered from the 0–15-cm soil layer in 1991 was approximately one-half the concentration recovered in 1990, but greater concentrations of fenamiphos sulfoxide (an oxidation product of fenamiphos) were recovered in 1991 than in 1990. Concentrations of fenamiphos, fenamiphos sulfoxide, and fenamiphos sulfone were near or below detectable levels (0.002 mg/kg soil) below the 0–15-cm soil layer. Rainfall treatments did not affect the efficacy of the nematicide against *Meloidogyne incognita* race 1. The concentration of fenamiphos in squash fruit in 1991 was below the detectable level (0.01 mg/kg).

Key words: Cucurbita pepo var. *melopepo,* degradation, efficacy, fenamiphos, leaching, *Meloidogyne incognita,* nematicide, nematode, pesticide residue, root-knot nematode, squash.

The most common nematicides used in the past to control nematodes on many vegetable crops in the United States were the soil fumigants, including ethylene dibromide (EDB), 1,2-dibromo-3-chloropropane (DBCP), and 1,3-dichloropropene (1,3-D) (8). With the suspensions of EDB and DBCP, nematicide use on vegetable crops has shifted to nonvolatile products, including fenamiphos, an organophosphate nematicide-insecticide.

Fenamiphos in soil is rapidly oxidized to fenamiphos sulfoxide (FSO), which is slowly oxidized to a sulfone (FSO_2) (14,17). FSO and FSO_2 have pesticidal activity and toxicity similar to that of fenamiphos (21), but FSO and FSO_2 are much more mobile (1,13) and persistent (18) in soils than fenamiphos. Degradation of fenamiphos varies with the history of soil exposure to the chemical (6,7,17), soil type (9,10), tillage methods (16), and microorganisms (18). Fenamiphos residue in soil does not persist longer than 30 days under field conditions (10,14,16).

There is increasing concern in the United States about pesticide movement in soil to contaminate groundwater and food products. In addition, growers are concerned about the effects of rainfall on nematicide efficacy. Information is not available on the effects of rainfall on degradation, leaching, efficacy, or residue in crops when rainfall occurs soon after nematicide application. The objective of this study was to determine the degradation, movement, and efficacy of fenamiphos in the soil and residue in squash fruit following simulated rainfall treatments after nematicide application under field conditions.

Materials and Methods

The experiment was established in field plots in April 1990 and repeated in the same plots in 1991 on Tifton loamy sand (fine-loamy, siliceous, thermic Plinthic Kandiudults; 85% sand, 10% silt, 5% clay; pH 6.0; 0.5% organic matter) infested with the southern root-knot nematode, *Meloidogyne incognita* race 1. The soil was disc-harrowed, plowed 25–30 cm deep with a moldboard plow, and shaped into beds 1.8

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m wide and 10–15 cm high. Fenamiphos (Nemacur 15G, Miles Inc., Kansas City, MO) was broadcast at 6.7 kg a.i./ha over plots and incorporated into the top 15-cm soil layer with a tractor-powered rototiller immediately before squash (*Cucurbita pepo* var. *melopepo*) cv. Dixie Hybrid was planted.

Simulated rainfall treatments were applied with a multiple-intensity rainfall simulator equipped with two 80150 Tee-jet nozzles calibrated to deliver 5 cm water/hour (15). Four rainfall treatments of 2.5 and 5.0 cm delivered 1 and 3 days after nematicides were applied on 1 and 3 May 1990 and 4 and 6 June 1991. Plots that received no rainfall, including those treated with fenamiphos and untreated, served as controls. Two glass containers were placed diagonally across each plot to measure and verify rainfall volume.

The experiment was a randomized complete block design with treatments replicated four times. Plots were single beds (2 rows) 1.8 m wide and 3 m long. Squash seeds were planted 30 cm apart in rows 0.91 m apart. Four soil cores 5-cm-d × 90 cm deep were collected from each plot 4 days after nematicide application with a hydraulic soil sampler mounted on a tractor. Each soil core was divided into segments corresponding to soil depths of 0–15, 15–30, 30–45, 45–60, and 60–70 cm in 1990 and 0–7.5, 7.5–15, 15–23, 23–46, and 46–70 cm in 1991. Soil from each core segment was weighed and a subsample was collected for moisture and bulk-density determinations. The subsamples were oven-dried (105 C) for 2 days. Gravimetric water content (g/g) was determined by the difference in the weights of moist and dried subsamples (3). Volumetric water content (cc/cc) was determined by multiplying the gravimetric water content by total weight (g) of soil in each core segment and water density (cc/g) divided by the total volume (cc) of the segment. Bulk density was calculated by dividing the total weight of oven-dry soil by the total volume of the segment. The four soil samples from the same depth and plot were mixed, placed in plastic bags, and stored moist in a freezer at −20 C until analyzed for fenamiphos, FSO, and FSO_2. Fenamiphos was added to untreated soil from control plots, which were stored as described for the field-treated samples, for use as calibration and recovery standards.

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 ml methanol was added to the flask and evaporated until dry. Finally, 2 ml acetonitrile was added to the flask, and the contents were passed through a syringe membrane filter into a high performance liquid chromatograph (HPLC) vial. Detection limits were 0.008 mg/kg soil for fenamiphos and 0.002 mg/kg soil for FSO and FSO_2.

Twenty soil cores (2.5-cm-d × 15 cm deep) were collected within the rows 8 May, 6 June, and 9 July 1990, and 21 July 1991 from each plot. The cores were composited and thoroughly mixed. A 150-cm^3 subsample was assayed for plant-parasitic nematodes by centrifugal-flotation (5).

Squash was hand-harvested 11 times from 8 June through 9 July 1990 and six times from 5 July through 12 July 1991. The fruit was separated into marketable fruits and culls, based on size and shape, and weighed. During the first harvest in 1991 (32 days after planting and application of fenamiphos), 10 squash fruits were selected arbitrarily from each treatment, packed in plastic bags, and stored in a freezer at −20 C until analyzed for total residue (fenamiphos, FSO, and FSO_2) (20). Fenamiphos was added to fruit samples from untreated plots, which were stored under similar conditions for use as calibration and recovery standards.

Two plants per plot were uprooted and rated for galls 45 days after planting in 1990. All plants were uprooted and rated for galls after the final harvest in 1990 and 1991. The root-gall index was based on a

1–5 scale: 1 = no galling, 2 = 1–25%, 3 = 26–50%, 4 = 51–75%, and 5 = 76–100% roots galled.

Data were subjected to analysis of variance, and the Waller-Duncan k-ratio *t*-test (where k = 100) was used to separate means (22). Regression analysis was used to relate nematode numbers to root-gall indices and root-gall indices to yield. Single-degree-of-freedom contrasts were used to compare certain treatments. Only statistically significant ($P \leq 0.05$) effects will be discussed unless otherwise stated.

Results and Discussion

Because no natural rainfall occurred during the first 8 days and 10 days of the test in 1990 and 1991, respectively, simulated rainfall will be referred to as rainfall hereafter. The mean measured rainfall rates were 2.4 ± 0.2 cm and 4.6 ± 0.6 cm in 1990 and 2.8 ± 0.1 and 5.6 ± 0.3 cm in 1991. Differences between the two rain gauges within plots averaged approximately 2 and 6 mm for the two rates, respectively. The volumetric water content in all plots increased with soil depth in 1990 and 1991 (Table 1). Water-content distribution was similar to "field capacity" (33 kPa) values presented by Hubbard et al. (4). The average moisture increase (Fig. 1) for the soil profile was 0.6 ± 0.1 cm or 23% of the 2.5-cm rainfall, and 2.0 ± 0.2 cm or 39% of 5-cm rainfall. Thus, the majority of the rainfall applied had left the profile by the time the soil was sampled, and the majority of that remaining was in the core segments from the deepest part of the samples. The 0–15-cm segments had apparently reached field capacity at sampling, and there was no difference between the two rainfall rates. Pan evaporation during the 3-day period between rainfall application and soil sampling averaged 6 mm/day in 1990 and 4 mm/day in 1991. The differences in soil moisture content between rainfall treatments applied 1 and 3 days after fenamiphos treatment were not significant (Table 1); thus, the major moisture loss was by percolation below the maximum depth sampled.

The mean bulk density (g/cc) at various soil depths was 1.19 (0–15 cm), 1.33 (15–30 cm), 1.45 (30–45 cm), 1.58 (45–60 cm), and 1.44 (>60 cm) and was not different

Table 1. Volumetric water content (cc/cc) in the soil at various depths 4 days after nematicide application, as influenced by volume and timing of simulated rainfall treatments in field plots in Tifton, Georgia, in 1990 and 1991.

Treatment			Soil depth (cm)				
Nematicide	Simulated rainfall (cm)	Days after nematicide treatment	1990 0–15	15–30	30–45	45–60	>60
Fenamiphos	0	—	0.055 c	0.087 b	0.125 c	0.158 b	0.221 a
Fenamiphos	2.5	1	0.073 ab	0.098 b	0.142 bc	0.156 b	0.202 a
Fenamiphos	2.5	3	0.071 b	0.098 b	0.146 abc	0.176 ab	0.208 a
Fenamiphos	5.0	1	0.076 ab	0.127 a	0.162 ab	0.207 a	0.259 a
Fenamiphos	5.0	3	0.081 a	0.129 a	0.166 a	0.209 a	0.245 a
None	0	—	0.057 c	0.101 b	0.132 c	0.167 b	0.222 a
	Treatment mean		0.069 z	0.107 y	0.145 x	0.179 w	0.226 v
			1991 0–7.5	7.5–15	15–23	23–46	>46
Fenamiphos	0	—	0.050 cd	0.077 c	0.090 a	0.117 b	0.224 a
Fenamiphos	2.5	1	0.069 ab	0.090 abc	0.110 a	0.136 b	0.216 a
Fenamiphos	2.5	3	0.080 a	0.096 ab	0.108 a	0.130 b	0.221 a
Fenamiphos	5.0	1	0.060 bc	0.084 bc	0.111 a	0.126 b	0.221 a
Fenamiphos	5.0	3	0.072 a	0.100 a	0.124 a	0.157 a	0.243 a
None	0	—	0.047 d	0.080 bc	0.100 a	0.120 b	0.226 a
	Treatment mean		0.063 z	0.088 y	0.107 x	0.131 w	0.225 v

Data are means of four replications. Means in columns and rows across treatments for each year followed by the same letter are not different according to the Waller-Duncan k-ratio *t*-test (k = 100).

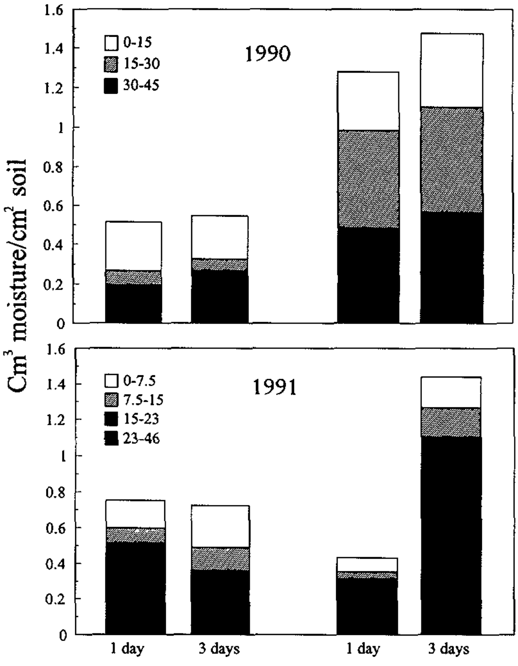

FIG. 1. Change in water content per unit area (cm^3 water per cm^2) in the soil profile after application of 2.5 and 5.0 cm simulated rainfall 1 and 3 days after fenamiphos treatment of field plots in Tifton, Georgia, 1990 and 1991.

among the treatments. Data on bulk density of the soil in this study were similar to those reported by Hubbard et al. (4).

In 1990 and 1991, 93% and 97%, respectively, of the fenamiphos recovered from treated plots was found in the 0–15-cm soil layer (Table 2). The plots treated with fenamiphos and no rainfall contained the greatest concentration of fenamiphos in the 0–15-cm soil layer. Seventy-six percent of the fenamiphos applied to those plots was recovered in 1990 and 43% in 1991. Generally, the fenamiphos concentration in the 0–15-cm soil layer was not affected by volume or timing of rainfall treatments. The data indicated that the rainfall treatments did not move the fenamiphos from the 0–15-cm soil layer to lower depths. Similar results have been reported (9,10,14). Experiments conducted in Dothan and Fuquay soils showed an accumulation of more than 90% of the fenamiphos in and recovered from the top 10-cm soil layer (16). Below the 15-cm soil depth, no differences were observed in concentrations of fenamiphos among treatments, except at the 30–45-cm depth in 1990, where concentrations in plots treated with fenamiphos and no rainfall

TABLE 2. Concentrations (mg/kg) of fenamiphos in the soil at various depths 4 days after application of fenamiphos as influenced by simulated rainfall timing and amount in field plots in Tifton, Georgia, in 1990 and 1991.

Treatment			Soil depth (cm)				
					1990		
Nematicide	Simulated rainfall (cm)	Days after nematicide treatment	0–15	15–30	30–45	45–60	>60
Fenamiphos	0	—	2.287 a	0.059 a	0.027 a	0.015 a	0.017 a
Fenamiphos	2.5	1	0.760 c	0.036 a	0.005 bc	0.002 a	0 a
Fenamiphos	2.5	3	0.937 bc	0.025 a	0.005 bc	0.004 a	0.002 a
Fenamiphos	5.0	1	0.924 bc	0.030 a	0.015 abc	0.005 a	0.006 a
Fenamiphos	5.0	3	1.365 b	0.021 a	0.020 ab	0.004 a	0.006 a
None	0	—	0.140 d	0.024 a	0.004 c	0 a	0.004 a
					1991		
			0–7.5	7.5–15	15–23	23–46	>46
Fenamiphos	0	—	1.238 a	0.086 a	0.029 a	0.021 a	0.004 a
Fenamiphos	2.5	1	0.907 a	0.096 a	0.348 a	0.014 a	0.003 a
Fenamiphos	2.5	3	0.609 a	0.040 a	0.027 a	0.020 a	0 a
Fenamiphos	5.0	1	0.783 a	0.114 a	0.043 a	0.021 a	0.016 a
Fenamiphos	5.0	3	0.435 a	0.085 a	0.039 a	0.017 a	0 a
None	0	—	0.114 a	0.130 a	0.016 a	0.031 a	0 a

Data are means of four replications. Means in columns for each year followed by the same letter are not different according to the Waller-Duncan k-ratio *t*-test (k = 100).

were greater than those in plots that received 2.5 cm rainfall (Table 2). Rainfall could have enhanced microbial activity that degraded fenamiphos to FSO. However, the concentrations of FSO in the 0–15-cm soil layer of all plots in 1990 were less than 0.25 mg/kg soil, below detectable levels at lower depths, and were not affected by rainfall treatments (data not included). In contrast, data collected in 1991 support the hypothesis of enhanced microbial degradation because greater concentrations of FSO than fenamiphos were recovered from the 0–15-cm soil layer in all nematicide-treated plots (Table 3). The percentage of fenamiphos recovered from the rainfall treatments ranged from 32 to 54 in 1990 and 27 to 47 in 1991. Concentrations of fenamiphos and FSO recovered are shown in Figs. 2 and 3. The fenamiphos concentrations observed in this experiment were in the same order of magnitude as those reported by Minton et al. (16). Movement of fenamiphos was similar to that reported (16), although no movement of fenamiphos was detected below the 15-cm depth and 5.0-cm rainfall after 4 days.

Lee et al. (13) reported that the half-life of fenamiphos was only 2 days in laboratory studies; the half-lives of the 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 a.i./ha (9). However, rapid movement of fenamiphos, FSO, and FSO_2 occurred in the 8–15-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). Concentrations of fenamiphos in the 8–15-cm soil

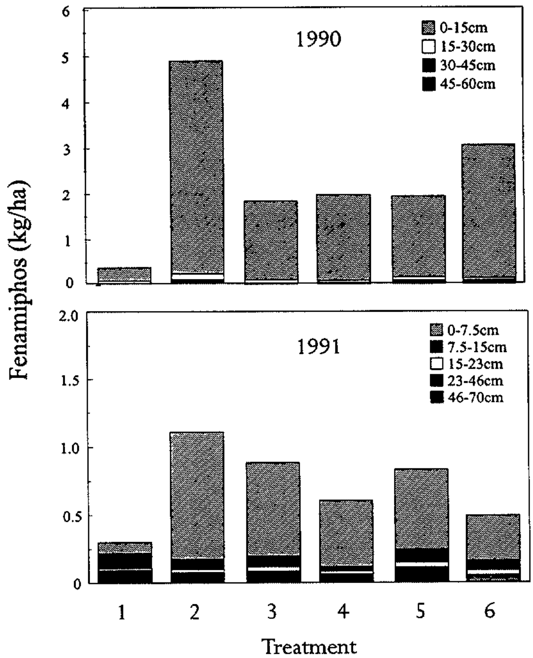

FIG. 2. Recoveries of fenamiphos (kg/ha) at various soil depths as influenced by 2.5 and 5.0 cm simulated rainfall applied 1 and 3 days after fenamiphos treatment. Treatment 1 = no rainfall, no fenamiphos; 2 = no rainfall, fenamiphos; 3 = 2.5 cm rainfall, 1 day after application of fenamiphos; 4 = 2.5 cm rainfall 3 days after application of fenamiphos; 5 = 5.0 cm rainfall, 1 day after application of fenamiphos; 6 = 5.0 cm rainfall, 3 days after application of fenamiphos. All fenamiphos treatments were 6.7 kg a.i./ha.

TABLE 3. Concentrations (mg/kg) of fenamiphos sulfoxide in the soil at various depths 4 days after application of fenamiphos, as influenced by simulated rainfall timing and amount in field plots in Tifton, Georgia, in 1991.

Treatment			Soil depth (cm)				
Nematicide	Simulated rainfall (cm)	Days after nematicide treatment	0–7.5	7.5–15	15–23	23–46	>46
Fenamiphos	0	—	2.139 a	0.300 a	0 a	0 a	0 a
Fenamiphos	2.5	1	2.514 a	0.546 a	0.017 a	0 a	0 a
Fenamiphos	2.5	3	1.923 a	0.294 a	0 a	0 a	0.003 a
Fenamiphos	5.0	1	2.124 a	0.604 a	0.091 a	0 a	0 a
Fenamiphos	5.0	3	1.203 ab	0.442 a	0.060 a	0.021 a	0 a
None	0	—	0.256 b	0.268 a	0 a	0 a	0 a

Data are means of four replications. Means in columns followed by the same letter are not different according to the Waller-Duncan k-ratio *t*-test (k = 100).

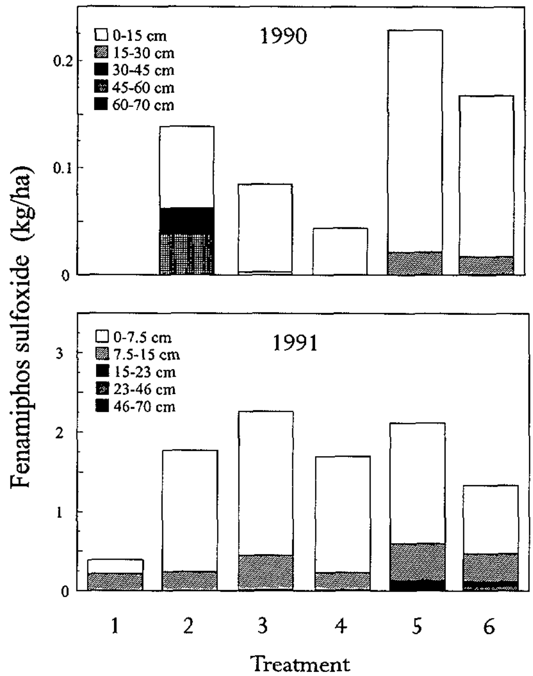

FIG. 3. Recoveries of fenamiphos sulfoxide (kg/ha) at various soil depths as influenced by 2.5 and 5.0 cm simulated rainfall applied 1 and 3 days after fenamiphos treatment. Treatment 1 = no rainfall, no fenamiphos; 2 = no rainfall, fenamiphos; 3 = 2.5 cm rainfall, 1 day after application of fenamiphos; 4 = 2.5 cm rainfall, 3 days after application of fenamiphos; 5 = 5.0 cm rainfall, 1 day after application of fenamiphos; 6 = 5.0 cm rainfall, 3 days after application of fenamiphos. All fenamiphos treatments were 6.7 kg a.i./ha.

depth increased from ca. 2 mg/kg soil on day 0 to ca. 5 mg/kg soil 1–3 days after application, but declined to 1 mg/kg soil 30 days after application (10). Ten days after application less than 0.01 mg/kg soil was recovered at depths below 15 cm.

Fenamiphos in soils with no history of previous exposure to the nematicide was degraded to CO_2 slowly, with less than 9% mineralized during 63 days of laboratory incubation (18). Both FSO and FSO_2 are much more mobile in soils than fenamiphos (1,13,16). Our data in 1991 indicated that concentrations of FSO in the 7.5–15-cm soil layer were less than 0.6 mg/kg soil and did not leach to lower depths (Table 3, Fig. 3). Concentrations of fenamiphos and FSO in the soil 4 days after application in 1991 were similar to those reported from other studies at this location 6 days after application of fenamiphos at the same rate (10,14).

Enhanced degradation of pesticides occurs in soils with a history of previous exposure to the chemical (17). Rohde et al. (19) detected the loss of almost all ethoprop within 5 days of application on a sandy loam, where ethoprop had been regularly applied in the 3 preceding years. This rapid loss may be a result of accelerated degradation by adapted microorganisms. The FSO concentrations were much higher in 1991 than in 1990 (Fig. 3) and represented the majority of the fenamiphos present. This difference may be explained by greater microbial degradation of fenamiphos, because the treatments in 1991 were superimposed on the same treatments in 1990. FSO is mobile and should have been flushed out of the system by the percolating water. Because the rainfall did not affect the concentrations of FSO or fenamiphos recovered from any soil depth in either year, apparently the FSO recovered from the top soil layers in 1991 was fenamiphos that was oxidized after the rainfall.

The numbers of *M. incognita* second-stage juveniles (J2) in the soil on each sampling date each year were positively correlated ($r = 0.43$ to $r = 0.87$, $P = 0.05$) with root-gall indices. Numbers of *M. incognita* J2 are not included. Root-gall indices of plants in fenamiphos-treated plots were lower than those in untreated plots on both sampling dates in 1990 (Table 4). The final root-gall indices of plants recorded 9 July 1990 in fenamiphos-treated plots that received 5.0 cm rainfall 3 days after nematicide application were lower than those from fenamiphos-treated plots that received 2.5 cm rainfall 1 day after nematicide treatment. Root-gall indices were negatively correlated ($r = -0.70$) with yield of marketable squash in 1990. In 1991, root-gall indices of plants in fenamiphos-treated plots that received 5.0 cm rainfall 1 and 3 days after nematicide application were lower than those from untreated plots, but not different from other treat-

TABLE 4. Root-gall indices and yield of squash, as influenced by fenamiphos and simulated rainfall treatments after nematicide application.

Treatment				Root-gall index[b]			Yield (Mt/ha)	
Number	Nematicide[a]	Simulated rainfall (cm)	Days after nematicide application	15 June 1990	9 July 1990	24 July 1991	1990	1991
1	Fenamiphos	0	—	1.88 b[c]	2.95 bc	3.42 ab	27.87 a	0.98 a
2	Fenamiphos	2.5	1	2.25 b	3.58 b	3.52 ab	28.48 a	0.65 a
3	Fenamiphos	2.5	3	1.75 b	3.00 bc	3.42 ab	29.76 a	0.98 a
4	Fenamiphos	5.0	1	1.75 b	2.90 bc	3.02 b	31.33 a	0.81 a
5	Fenamiphos	5.0	3	1.50 b	2.45 c	2.92 b	29.98 a	1.30 a
6	None	0	—	4.88 a	4.93 a	4.25 a	16.73 b	0.98 a
Single-degree-of-freedom contrast:								
2 + 3 vs. 4 + 5				ns	ns	ns	ns	ns
2 + 4 vs. 3 + 5				ns	ns	ns	ns	ns
6 vs. other treatments				**	*	*	**	ns

[a] Fenamiphos 15G applied at 6.7 kg a.i./ha.
[b] Percentage root galling, indexed on a 1–5 scale as follows: 1 = no galls, 2 = 1–25%, 3 = 26–50%, 4 = 51–75%, and 5 = 76–100%.
[c] Means followed by the same letter are not different ($P \leq 0.05$); * = ($P \leq 0.05$), ** = ($P \leq 0.01$), and ns = nonsignificant ($P \leq 0.05$).

ments. Single-degree-of-freedom contrasts showed no differences in root-gall indices in either year between volumes of rainfall and days after nematicide application. In 1991, the root-gall indices were positively correlated with yield of cull squash (r = 0.82) and negatively correlated with yield of marketable squash (r = −0.31).

Yields of squash in 1990 from plants in all nematicide-treated plots were greater than those from untreated plots and were not affected by rainfall treatments (Table 4). Yields were lower in 1991 than 1990 and were not different among treatments. Single-degree-of-freedom contrasts showed no differences in yields in either year between volumes of rainfall and days after nematicide application.

The efficacy of fenamiphos was not affected by rainfall treatments in 1990. The root-gall indices and yield of squash in 1990 were similar to those reported in other studies (10–12). The low yield of squash in 1991 was due, in part, to high soil temperatures (26–38 C in upper 5-cm soil layer during the first 20 days of the experiment), which may have affected pollination and fruit-set, but the total cause is unknown.

Concentrations of fenamiphos in squash fruit 32 days after fenamiphos application were below the detectable level of 0.01 mg/kg. This concentration of fenamiphos residue in squash fruit is far below the tolerance established for fenamiphos on other vegetable crops: cabbage, 0.10 mg/kg; eggplant, 0.10 mg/kg; okra, 0.30 mg/kg; and non-bell pepper, 0.60 mg/kg (2).

Data from this experiment may be used to caution against retreatment of fenamiphos by growers who may think that 2.5–5.0 cm rainfall 1–3 days after application may leach fenamiphos from the site needed for maximum nematode control. More research is needed on the effects of soil moisture and other factors on degradation of fenamiphos to manage nematodes on other crops.

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