Response of Phytoparasitic and Free-Living Nematodes to Soil Solarization and 1,3-Dichloropropene in California

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To simplify information, trade names of products have been used. Neither endorsement of named products nor criticism of similar products not mentioned is intended.

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ABSTRACT

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Ten field sites in the California counties of Merced, Napa, Sonoma, and Yolo were preplant or postplant treated for 4–6 wk with soil solarization and/or 56–150 L of Telone II (50–100% label dosage of 92% 1,3-dichloropropene [=1,3-D]) per hectare. Results of soil assays immediately following treatment by solarization and solarization plus 1,3-D included significant population density reductions of 42–100% of *Meloidogyne, Heterodera, Pratylenchus, Paratrichodorus, Criconemella, Xiphinema*, and *Paratylenchus* spp., total phytoparasitic nematodes, and total phytoparasitic plus free-living nematodes, compared to nontreated control soil. Nematode population density reductions following treatment by 1,3-D alone were usually significantly less. At two of the sites, moist soil covered by polyethylene film was shaded from solar heating by sheets of gypsum board (sheetrock building construction wallboard). Subsequent soil assays from the shaded treatments showed significant population density reductions that were approximately half of those attained following solarization, indicating partial control directly or indirectly due to the polyethylene film cover and/or maintaining high soil moisture during the treatment. Several months after solarization, population density reductions were usually greater than those found immediately following treatment, even when susceptible crops were planted in the soil during the interim period. At one site, significant population density reductions of *Helicotylenchus digonicus* were found in solarized plots 3 mo after, but not immediately after treatment. Soil was assayed to a maximum depth of 91 cm. Field and greenhouse-grown plants usually showed significant increased growth responses in solarized (32–128%) or solarized plus 1,3-D-treated (43–152%) soil, as compared to nontreated control soil; but not by 1,3-D alone, or from orchard trees at postplant-treated sites.

Additional key words: *Capsicum annuum*, nematode control, soil heating.

Soil solarization, a method of hydrothermal soil disinfestation using solar energy to heat moist soil covered by polyethylene film, has controlled several fungal plant diseases and weed pests (9,10,18), and reduced population densities of a wide range of soilborne microorganisms (20). A few reports of phytoparasitic nematode control by this method have been made (7,19), as well as other reports of inconclusive or negative results (10,17). The use of heat as a method of killing nematodes is well established (4,11,16), and hot water treatments for controlling nematodes in seed and planting stock are routine (6,12,13,23). Most of the information on nematode response to solarization, however, has been restricted to endoparasitic phytonematodes. Also, soil sampling for determination of nematode response has been confined to the upper 30 cm or less. Information on response of nematodes deeper in the soil is lacking.

This 3-yr study (1980–1982) examined the response of soil nematodes, particularly phytoparasites, to soil solarization over a wide range of experimental parameters, including nematode genera and feeding habit, cropping, extent of soil heating, soil type, and depth of nematode populations in soil. In addition, the use of Telone II (92% 1,3-dichloropropene [=1,3-D]) was added to the study at some sites, to test for increases of nematode control when combined with solarization, and as an indicator of control by solarization alone. A preliminary report was published (21).

MATERIALS AND METHODS

Field treatment application. Ten field sites in the California counties of Merced, Napa, Sonoma, and Yolo during 1980–1982 were used. All sites were prepared by disking and rolling, or floating the soil to seedbed consistency. Effective depth of pretreatment preparation was usually 20 cm. Soil was either preirrigated, or flooded under the clear polyethylene film (0.025 mm thickness), which was used at all sites, with 5–15 cm of water, which was sufficient to wet the soils throughout the selected sampling depths.

When 1,3-D was applied, either a partial (56 or 122 L/ha) or approximate full (140 or 150 L/ha) label dosage for each particular crop and soil type was used. Fumigant was applied either with a handpump (Fumigun; Neil A. Maclean Co., San Francisco, CA [now insolvent—equipment not available]), or a tractor-mounted gas-pressured fumigator with chisels set 30 cm apart. Application depth of 1,3-D was normally 20 cm, and treated soil was sealed by irrigation water and/or polyethylene film when combined with solarization, or mechanical compaction. Three to 10 replications of each treatment was used at each field site, and replications were normally a minimum of 3 × 6 m. Air and soil temperatures were monitored during most experiments. Due to the experimental variation at the different field sites, they will be described individually.

Field experiments. *Site 1 (Winton, Merced County) (14 July–11 August 1980).* This experiment was located in a 3-yr-old block of almond trees, cultivar Merced on Lovell peach rootstock. The soil type was Atwater sand. The site was preirrigated and polyethylene film was laid in a 6-m square around each treated tree. After 4 wk of treatment, plastic was removed, and soil samples were taken in depth ranges of 0–22 cm and 22–46 cm. Soil samples were taken again 7 mo later. Tree circumferences 30 cm above the soil line on the trunk were taken when the plastic was removed, and again 1 yr later.

Site 2 (Atwater, Merced County) (14 July–13 August 1980). Experimental procedure and soil type were the same as at Site 1 except the orchard was a 6-yr-old block of peach trees, cultivar Fay

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Elberta on Nemaguard peach rootstock.

Site 3 (Rutherford, Napa County) (13 July–24 August 1981). A mature grape vineyard was removed approximately 2 mo prior to soil solarization. Undecomposed roots were present in the soil at the time of treatment. The soil type was Cortina very gravelly loam. Soil was preirrigated prior to treatment. Soil samples at 0–30 and 30–61 cm depth ranges were taken only immediately following treatment.

Site 4 (Davis, Yolo County) (14 July–27 August 1981). A mature walnut orchard was removed 6 mo prior to soil solarization and other treatments. Undecomposed roots remained in the soil. The soil type was Reiff loam. Treatments of the fallowed soil included solarization (S), 1,3-D (122 L/ha—approximately 50% label dosage) (T), solarization plus 1,3-D (ST), and untreated control (C). Irrigation water was flooded under the film. Following treatment, soil from the 0–23 cm depth range of each treatment was taken to the greenhouse and placed in 15-cm-diameter pots. Tomato (*Lycopersicon esculentum* 'Earlypak 7') plants were grown (one plant per pot) for 6 wk to assay for possible increased growth responses resulting from soil treatments. Five pots per treatment were used. Plants were then excised at the soil line, placed in a draft oven, and dry weights were taken. Also, rooted cuttings of grapevine (*Vitis vinifera* 'Sauvignon blanc,' and *Vitis rupestris* 'St. George') were planted into the plot 7 mo after treatment as indicators of nematode recolonization ability and plant growth response to treatments. Six months after planting, indicator grapevines were undercut, and roots were excised at the soil line. Fresh shoot growth weights of both grape cultivars were taken, and root samples of cultivar St. George were extracted to obtain root populations of *Pratylenchus vulnus*. Soil samples were taken at 0–46 and 46–92 cm depth ranges following treatment, and again 14 mo later.

Site 5 (Davis, Yolo County) (15 July–25 August 1981). A 3-yr-old stand of alfalfa (*Medicago sativa* 'Lahontan') was disked under 3 mo prior to treatment of the plot. Soil type and treatments were the same as those described above for Site 4. Two months after treatment, cultivar Lahontan alfalfa was again seeded into the plot. Soil samples were taken following treatment, and also 8 mo later to assay changes in nematode population densities.

Site 6 (Esparto, Yolo County) (18 July–1 September 1981). Sugar beets were harvested from this site, on Marvin silty clay loam, approximately 3 mo prior to soil solarization. Treatments were as described for Site 4. Six weeks after treatment, soil samples were taken in 0–23 and 23–46 cm depth increments, bulked by treatment, and planted to tomato in the greenhouse as described for the Davis walnut site. Top growth dry weights were taken 6 wk later.

Site 7 (Healdsburg, Sonoma County) (28 July–13 August 1981). This experiment was located in a 15+-yr-old block of prune trees, cultivar French on Marianna 2624 plum rootstock. The soil type was Yolo loam. Treatments were as previously described for Site 4. Polyethylene film, where used, was placed in a 6-m square around third leaf replant trees. Soil samples were taken to 46 cm depth following treatment. Tree trunk circumferences were taken following treatment, and again 12 mo later.

Site 8 (Davis, Yolo County) (19–29 September 1981). This site was a field fallowed for 2 mo after turning under safflower stubble. The soil type was Reiff fine sandy loam. Treatments included soil solarization (S), moist soil covered with clear polyethylene film, but shaded by sheets of 1.25-cm-thick gypsum sheetrock (building construction wallboard) placed over the plastic to prevent solar heating (treatment will hereafter be referred to as "shaded") (SH), and untreated soil (C). Water was applied by flooding under the plastic film. Following treatment, strawberry (*Fragaria chiloensis* 'Tufts') rooted cuttings were transplanted into the site. Soil samples (0–22 cm and 22–46 cm depth ranges) were taken following treatment, and again 9 mo later to assay nematode population densities.

Site 9 (Woodland, Yolo County) (27 August–29 September 1981). Sugar beets were harvested 2 mo prior to soil treatment. Experimental plots were laid out on an area where severe stunting had been observed and was probably due to the sugar beet cyst nematode (*Heterodera schachtii*). Preliminary soil samples contained nematode cysts. The soil type was Sycamore silty clay loam. Size of treatment replications were 1-m square. Treatments included two 1,3-D rates (56 L/ha [partial label dosage], and 150 L/ha [approximately full label dosage]) and two depths of fumigant placement (10 and 30 cm), with and without solarization, as well as solarization alone, and a nontreated control. Plots were flood irrigated after application of plastic film. Following treatment, soil samples of 0–30 cm depth were taken, returned to the greenhouse, and three 500-ml aliquots from each sample were placed in 15-cm-diameter pots. Each pot was transplanted with a sugar beet (*Beta vulgaris* 'USH-11') seedling. Six weeks after transplanting, soil and roots from pots were sieved and assayed for "white female" sugar beet nematodes.

Site 10 (Davis, Yolo County) (16 June–26 July 1982). The experimental site was a field fallowed 9 mo since cropping to tomato. The soil type was Yolo loam. Treatments included soil solarization, 1,3-D (140 L/ha, approximately full label dosage), solarization plus 1,3-D, shaded, shaded plus 1,3-D, and untreated soil. Soil was flooded with water under the film. Following treatment, pepper seedlings (*Capsicum annuum* 'Early Jalapeno,' 'Resistant Giant,' and 'Pimiento L' [Peto Seed Co., Inc., Woodland, CA 95695]) were transplanted into the site. Soil samples were taken at 0–22 and 22–46 cm depth ranges following treatment, and again 3 mo later to determine changes in nematode population densities.

Nematode sampling and assays. Immediately following the removal of the polyethylene film, soil samples were taken. Additional samples were taken at some sites 3–14 mo after treatment. Normally, four to eight cores (25 mm in diameter), randomly spaced, per replication were taken to the desired sampling depth with a standard soil tube, bulked by replication and depth in polyethylene bags and returned to the laboratory in ice chests. Nematodes were extracted from soil by mixing the samples thoroughly, and subjecting 250 ml of soil to the centrifugal flotation extraction (8), or the sieving and Baermann funnel method (5). Root tissue samples were extracted by dicing the roots and incubating them under warm, intermittent mist (14). Extracted nematodes were then enumerated under a stereo dissecting microscope and identified. Other methods of sampling and assay are described in the individual experiments.

TABLE 1. Air temperatures nearest field sites during soil solarization experiments in California, 1980–1982[a]

Site	California location	Dates	Temperatures (C) Avg. max.	Avg. min.	High max.
1&2	Winton/Atwater[b]	July–August 1980	35	16	41
3	Rutherford[c]	July–August 1981	32	13	42
4&5	Davis	July–August 1981	34	12	41
6	Esparto[d]	July–August 1981	38	13	46
7	Healdsburg	August–September 1981	32	12	42
8	Davis	August–September 1981	32	12	37
9	Woodland	August–September 1981	34	14	38
10	Davis	June–July 1982	31	12	37

[a] Data from National Oceanic and Atmospheric Administration. Environmental Data and Information Service, National Climatic Center, Asheville, NC.
[b] Data collected at Merced, CA (~10 mi from plots).
[c] Data collected at Saint Helena, CA (~5 mi from plot).
[d] Data collected at Capay, CA (~5 mi from plot).

RESULTS

Air and soil temperatures. Air temperatures for each field site are given in Table 1. Air temperature data are taken from those collected by the National Oceanic and Atmospheric Administration (NOAA) climatological station nearest each field plot. These data are included to indicate approximate air temperatures only. Actual field plot temperatures may have varied somewhat from those reported here. Maximum soil temperatures from several of the experimental sites are shown in Table 2.

Field experiments. *Site 1.* Soil samples collected immediately after treatment showed that *Criconemella xenoplax, Paratrichodorus porosus, Paratylenchus hamatus*, and total plant-parasitic nematodes had been reduced 61–96% by solarization, as compared to controls in the entire 0–46 cm sampling depth around the trees. *Pratylenchus vulnus* was significantly reduced by 75% in the 0–23 cm depth range only. When plots were sampled again 7 mo later, only *P. porosus* remained at a significantly lower population density (65% lower) than in control soil. *P. hamatus* recolonized treated plots to the greatest degree. Root populations of *P. vulnus* were very low in all treatments. No injury to trees resulting from treatment was observed. No significant differences in tree growth between treatments was seen 1 yr after solarization.

Site 2. Results were similar to those obtained from Site 1. *C.*

TABLE 2. Maximum soil temperatures during soil solarization treatment periods at seven field sites in California, 1980–1982

Site	California location	Dates	Treatment	Maximum temp at 15 cm	30 cm	46 cm
2	Atwater	14 July–13 August 1980	Solarized (full sun)	45	38	···[a]
			Solarized (under tree canopy)	38	···	···
			Control (full sun)	37	31	···
			Control (under tree canopy)	31	···	···
4	Davis	14 July–27 August 1981	Solarized (full sun)	44	36	···
			Control (full sun)	35	30	···
6	Esparto	18 July–1 August 1981	Solarized	···	···	36
			Control	···	···	28
7	Healdsburg	28 July–13 October 1981	Solarized (full sun)	37	···	30
			Control (full sun)	36	···	22
8	Davis	19 August–29 September 1981	Solarized	39	···	35
			Shaded	30	···	25
			Control	32	···	27
9	Woodland	27 August–29 September 1981	Solarized	37	···	···
			Control	30	···	···
10	Davis	16 June–26 July 1982	Solarized	44	···	···
			Shaded	···	···	···
			Control	34	···	···

[a]··· = No data.

TABLE 3. Greenhouse growth responses of tomato plants following soil solarization at two field sites in California, 1981

Site	Location	Treatment dates	Soil treatment	Plant dry wt. (g/plant)	Increase over control (%)
4	Davis	14 July–27 August	Solarized + 1,3-D[y]	4.3	87 a[z]
			Solarized	4.2	83 a
			1,3-D	2.0	−13 b
			Control	2.3	··· b
6	Esparto	18 July–1 September	Solarized + 1,3-D	4.2	50 a
			Solarized	4.6	64 a
			1,3-D	3.0	7 b
			Control	2.8	··· b

[y]Fumigation with 1,3-D was at 122 L/ha in each case.
[z]Values followed by different letters are different ($P \leq 0.05$) according to Duncan's multiple range test.

TABLE 4. Growth responses of field-grown peppers following preplant soil solarization in California, 1981–1982

Year, site, cultivar	Treatment	Fruit yields: Pod weight (fr.wt. [g]/plant)	Increase over control (%)	Pod weight (fr.wt. [kg/ha])[x]	Increase over control (%)	Vegetative growth: Surviving plants (%)	Increase over control (%)	Fresh weight (fr.wt. [g]/plant)	Increase over control (%)
1982, Davis, (site 10)									
Early Jalapeno	Solarized + 1,3-D[y]	221.7	99.5 a[z]	7,355.2	129.9 a	92	15.0 a	103.6	152.1 a
	Shaded + 1,3-D	188.1	69.3 ab	6,338.6	98.1 a	93	16.3 a	80.2	95.1 bc
	Solarized	183.1	64.8 ab	5,979.8	86.9 a	90	12.5 a	94.4	129.7 ab
	Shaded	167.1	50.9 bc	5,337.0	66.8 a	90	12.5 a	68.4	66.4 cd
	1,3-D	120.1	8.1 cd	3,049.7	−4.7 b	70	−12.5 b	51.2	24.6 de
	Control	111.1	0.0 d	3,199.2	0.0 b	80	0.0 ab	41.1	0.0 e
Pimiento L	Solarized + 1,3-D	353.8	33.0 a	12,504.3	112.0 a	98	58.1 a	379.1	43.1 a
	Shaded + 1,3-D	357.6	34.4 a	11,487.2	94.7 a	90	45.2 a	273.4	3.2 b
	Solarized	305.9	15.0 ab	9,683.3	64.1 ab	83	33.9 a	350.6	32.4 a
	Shaded	371.2	39.5 a	11,812.7	100.2 a	88	41.9 a	292.4	10.4 b
	1,3-D	261.4	−1.7 b	7,567.6	28.3 bc	80	29.0 ab	294.1	11.0 b
	Control	266.0	0.0 b	5,899.5	0.0 c	62	0.0 b	264.9	0.0 b

[x]Pod fresh wt. (grams per plant) × surviving plants per hectare.
[y]The fumigant 1,3-dichloropropene (1,3-D) was applied at 140 L/ha throughout this experiment.
[z]Values followed by different letters are different ($P \leq 0.05$) according to Duncan's multiple range test.

xenoplax and *P. porosus* were the predominant phytoparasitic nematodes found, while *P. hamatus* and *P. vulnus* were detected in low numbers. Due to the increased canopy cover from the older and larger trees, the extent of solar heating was probably less here than at the Winton site. Soil temperatures at a depth of 15 cm were 6–7 C cooler under the tree canopy than those without shading (see Table 2). Significant nematode population density reductions were mainly limited to the 0–23 cm depth range. When compared to controls, only densities of *C. xenoplax* were significantly reduced following solarization (44%) throughout the 0–46 cm sampling

TABLE 5. Effect of soil solarization and/or 1,3-dichloropropene (1,3-D) on population densities of soilborne nematodes in California

Year and site Nematodes	Treatment	Nematodes per 100 cc of soil after treatment 1 day, at soil depths (cm) 0–23[w]	23–46	0–46	7 mo, at soil depths (cm) 0–23	23–46	0–46
980, Winton (site 1)							
Criconemella xenoplax	Control	5.1	11.8	8.5	4.4	17.1	10.8
	Solarized	1.2	0.9	1.1*[x]	2.4	3.0	2.7
Paratrichodorus porosus	Control	30.5	27.5	29.0	3.8	17.6	10.7
	Solarized	14.6	8.0*	11.3*	2.1	5.5*	3.8*
Pratylenchus vulnus	Control	10.6	25.0	17.8	2.7	1.9	2.3
	Solarized	2.7	4.2	3.5	0.8	0.8	0.8
Pratylenchus hamatus	Control	2.8	42.4	22.6	1.7	14.3	8.0
	Solarized	2.0	0*	1.0*	12.6	18.8	15.7
Total phytoparasitic	Control	54.4	106.7	80.5	12.6	50.9	63.5
	Solarized	20.9	13.2*	17.0	17.8	28.1	45.9
1980, Atwater (site 2)							
C. xenoplax	Control	97.3	100.6	99.0	5.2	9.7	7.5
	Solarized	22.4*	88.2	55.3*	4.3	6.7	5.5
P. porosus	Control	33.5	55.0	44.3	4.8	11.8	8.4
	Solarized	19.5*	39.5	29.5	3.9	10.5	7.2
Total phytoparasitic	Control	138.3	159.4	148.9	12.5	24.5	18.5
	Solarized	62.4*	136.3	99.4	14.3	21.7	18.0
		1 day, at soil depths (cm)					
1981, Rutherford (site 3)		0–30	30–61	0–61			
Xiphinema spp.	Control	1.7	2.0	*1.9*			
	Solarized	0.3*	0.7	*0.5**			
		1 day, at soil depths (cm)			12 mo, at soil depths (cm)		
		0–46	46–91	0–91	0–46	46–91	0–91
1981, Davis (site 4)							
C. xenoplax	Control	27.9	100.1	64.0	27.8 a[y]	76.3	52.1 a
	1,3-D (122 L/ha)[z]	8.9	102.1	55.5	17.9 ab	92.9	55.4 a
	Solarized	10.8	177.6	94.2	0.7 b	15.2	7.9 b
	Solarized + 1,3-D	5.8	152.2	79.0	0.6 b	73.5	21.1 b
P. vulnus	Control	30.0 a	34.4	32.2	10.6	34.6	45.2 a
	1,3-D	10.2 b	35.4	22.8	11.8	28.0	39.8 a
	Solarized	1.2 b	30.4	15.8	0.4	10.9	11.3 b
	Solarized + 1,3-D	0.2 b	19.4	9.8	0.1	7.3	7.4 b
		1 day, at soil depths (cm)			8 mo, at soil depths (cm)		
		0–46	46–91	0–91	0–46	46–91	0–91
1981, Davis (site 5)							
Meloidogyne hapla	Control	28.6 a	40.0	34.5	40.4 a	113.2 a	76.8 a
	1,3-D (122 L/ha)	8.7 b	37.8	23.3	1.7 b	30.6 b	16.2 a
	Solarized	6.3 b	29.0	17.7	0.5 b	0.9 b	0.7 b
	Solarized + 1,3-D	0.0 b	16.6	8.3	0.3 b	10.3 b	5.3 b
Total phytoparasitic	Control	45.6 a	43.7	44.7	64.9	115.8 a	90.4
	1,3-D	17.7 b	56.2	37.0	55.7	31.0 b	43.4
	Solarized	11.6 b	29.8	20.7	112.0	1.6 b	56.8
	Solarized + 1,3-D	1.9 b	17.4	9.7	9.0	10.4 b	9.7
Total phytoparasitic plus free-living	Control	91.1 a	72.7	81.9 a	251.7	137.0 a	206.9 a
	1,3-D	49.9 b	59.5	54.7 b	202.9	54.1 a	128.5 ab
	Solarized	23.7 bc	36.4	30.1 c	191.9	9.0 b	100.5 b
	Solarized + 1,3-D	11.9 c	23.8	17.9 c	96.5	17.5 b	57.0 b

(continued on next page)

depth. No reductions were found when the site was sampled 7 mo after treatment. No injury to trees or fruit load was seen during or following solarization. As noted for Site 1, no differences between treatments in tree growth were observed 1 yr after solarization.

Site 3. The only phytoparasitic nematodes found were *Xiphinema* spp. When the film was removed, population densities of these dagger nematodes had been significantly reduced by 82% in the 0–30 cm sampling depth range, and by 74% in the overall 0–61 cm range, compared to those in nonsolarized soil.

Site 4. High population densities of *Pratylenchus vulnus* and

TABLE 5. (continued)

Year, site, crop Nematodes	Treatment	Nematodes per 100 cc of soil after treatment					
		1 day, at soil depths (cm)			7 mo, at soil depths (cm)		
		0–23[w]	23–46	0–46	0–23	23–46	0–46
		1 day, at soil depths (cm)					
		0–23	23–46	0–46			
1981, Esparto (site 6)							
Total phytoparasitic plus free-living	Control	128.5 a	108.0 a	118.3 a			
	1,3-D (122 L/ha)	109.1 a	48.2 b	78.7 a			
	Solarized	5.8 b	3.1 b	4.5 b			
	Solarized + 1,3-D	7.1 b	15.8 b	11.5 b			
				1 day, at soil depths (cm)			
				0–46			
1981, Healdsburg (site 7)							
Paratylenchus neoamblycephalus	Control			37.3			
	1,3-D (122 L/ha)			47.5			
	Solarized			48.0			
	Solarized + 1,3-D			29.3			
Total phytoparasitic	Control			39.5			
	1,3-D			52.8			
	Solarized			50.6			
	Solarized + 1,3-D			30.2			
Total phytoparasitic plus free-living	Control			108.1			
	1,3-D			130.3			
	Solarized			112.9			
	Solarized + 1,3-D			61.1			
		1 day, at soil depths (cm)			9 mo, at soil depths (cm)		
		0–23	23–46	0–46	0–23	23–46	0–46
1981, Davis (site 8)							
Total phytoparasitic plus free-living	Control	174.7 a	41.2	108.0 a	125.9 a	40.3	83.1
	Solarized	18.9 b	10.8	14.9 b	51.7 b	13.2	32.5
	Shaded	99.9 ab	23.1	61.5 ab	65.7 b	14.7	40.2
		1 day, at soil depths (cm)			3.5 mo, at soil depths (cm)		
		0–23	23–46	0–46	0–23	23–46	0–46
1982, Davis (site 10)							
Helicotylenchus digonicus	Control	10.7	1.7	6.2	4.4 a	5.1	4.8 a
	1,3-D (140 L/ha)	3.2	0.9	2.1	0.5 b	1.7	1.1 bc
	Solarized	1.3	1.9	1.6	1.3 b	1.8	1.6 bc
	Shaded	4.7	2.0	3.3	1.4 b	4.6	3.0 ab
	Solarized + 1,3-D	0.3	1.3	0.8	0.1 b	1.0	0.6 bc
	Shaded + 1,3-D	0.7	1.0	0.8	0.2 b	0.1	0.2 c
Total phytoparasitic	Control	13.2	9.2	10.9	4.5 a	11.7	8.1
	1,3-D (140 L/ha)	4.0	2.3	3.1	0.4 b	3.0	1.7
	Solarized	3.1	7.9	5.5	1.3 b	4.2	2.8
	Shaded	5.2	12.0	8.6	1.5 b	10.2	5.9
	Solarized + 1,3-D	0.4	7.0	3.7	0.1 b	5.5	2.8
	Shaded + 1,3-D	2.2	18.5	10.4	0.5 b	2.7	1.6
Total phytoparasitic plus free-living	Control	96.5 a	44.5	70.5 a	83.9 a	29.0	56.5 a
	1,3-D (140 L/ha)	43.3 b	6.4	25.2 bc	21.3 c	8.3	14.8 b
	Solarized	17.7 bc	20.4	19.4 c	28.5 c	14.8	21.7 b
	Shaded	49.8 b	37.7	43.7 b	68.5 ab	29.9	49.2 a
	Solarized + 1,3-D	7.1 c	19.4	13.2 c	24.1 c	16.1	20.1 b
	Shaded + 1,3-D	32.6 bc	33.9	33.3 bc	38.9 bc	14.8	26.6 b

[w] Soil sample depth range (cm).
[x] * = Value different from control at ($P \leq 0.05$) according to Student's *t*-test.
[y] Values followed by different letters are different at ($P \leq 0.05$) according to Duncan's multiple range test.
[z] Dosages of 1,3-D shown are the same as when combined with other treatments.

Criconemella xenoplax were found here in nontreated soil. Soil was sampled to 91 cm depth. In soil collected immediately following treatment, population densities of *P. vulnus* had been significantly reduced by treatment (S) (96%), (T) (66%), and (S+T) (99%) in the 0–46 cm depth range only, when compared to controls. No reductions in populations of *C. xenoplax* by any treatment or at any depth were found.

Marked differences in tomato plant and grapevine growth were observed. Tomato plants grown in the greenhouse in soil from this site that was treated by (S), or (S+T) were significantly heavier (83–87%) than plants grown in (T)-treated soil or control soil when plant dry weights were taken. Greenhouse plant growth data are summarized in Table 3.

When grapevines grown at this field site were undercut, no significant differences between treatments in shoot growth of cultivar Sauvignon blanc were found. However, cultivar St. George vines showed an unexplained 44% decrease after the (S+T) treatment. Root extractions of *P. vulnus* showed population density reductions of 76–99% following all three treatments, as compared to roots from the untreated control vines. Nematode extractions from soil 1 yr after treatment showed that (S) plots had significant reductions of *C. xenoplax* (85%) and *P. vulnus* (75%), and (S+T)-treated plots had fewer *C. xenoplax* (60%) and *P. vulnus* (84%), in the overall 0–91 cm depth range, than did the nontreated control plots. Population densities in plots treated by (T) alone were not significantly different from untreated plots.

Site 5. Several phytoparasitic nematodes, including *Meloidogyne hapla, Pratylenchus* spp., and *Xiphinema* spp., as well as two unidentified Tylenchorhynchidae, were recovered from soil at this site. *M. hapla* was the predominant nematode found, especially in the 46–91 cm depth range. Following termination of the treatments, total (phytoparasitic plus free-living) nematodes, total phytoparasitic nematodes, and *M. hapla* were all reduced in population density (45–100%) by treatment with (S) and/or (T) in the upper 46 cm of soil compared with the control treatment. Only total nematodes were reduced significantly throughout the 0–91 cm sampling depth range, by the (T) (33%), (S) (63%), and (S+T) (78%) treatments. Seven months after alfalfa was replanted in the plots, soil was again sampled. Total nematodes and *M. hapla* were significantly lower in population density in (S) (51–99%) or (S+T)-treated (72–93%) plots in the entire 91 cm sampling depth only, compared with the control treatment. Population density reductions were seen for all three nematode taxa in the 46–91 cm soil depth range, but only *M. hapla* was significantly reduced in the upper 46 cm of soil.

Site 6. Population densities of total phytoparasitic plus free-living nematodes were significantly reduced by 90–97% in all depth ranges sampled following treatment by (S) and (S+T), compared with the control treatment. Treatment by (T) alone significantly reduced populations (55%) in the 23–46 cm depth range only. Top growth of greenhouse-grown tomatoes was significantly heavier for plants grown in (S) (64%) and (S+T) (50%) soils than plants grown in control soil (Table 3).

Site 7. Soil temperature data from solarized plots indicated that temperature increases at 15 cm depth were 6–8 C lower than those encountered at warmer central valley sites, such as sites 2 or 6 (see Table 2). The predominant phytoparasitic nematode found was a pin nematode, *Paratylenchus neoamblycephalus*. Soil samples taken to 46 cm depth showed no significant differences among population densities of total nematodes, total phytoparasitic nematodes, or *P. neoamblycephalus* for any of the treatments used. No apparent injury to the prune trees resulted from treatment by solarization and/or 1,3-D. Tolerance of low doses of 1,3-D by orchard trees has been previously reported (25). Tree trunk circumference measurements 1 yr after treatment indicated that no significant growth changes resulted from any treatment.

Site 8. When soil and roots in pots were assayed after 6 wk growth of sugar beet plants, population densities of sugar beet cyst nematode (*Heterodera schachtii*) "white females" were found to have been significantly reduced by at least 63% following all treatments, as compared to the untreated controls. No differences in nematode counts between different rates or placement depths of 1,3-D were found. When all of the 1,3-D alone treatments were compared to all of those combining solarization and 1,3-D, the reductions due to treatments of 1,3-D alone compared with the untreated control averaged 87%, while those combining solarization and 1,3-D averaged 99%. This site was treated in September (late in the warm season), and soil heating was much less than might be expected during midsummer, so the efficacy of solarization during this experiment was probably not optimal.

Site 9. No generally-distributed phytoparasitic nematodes were recovered from this experimental site. *Helicotylenchus digonicus* and *Xiphinema* spp. were occasionally found. This site was also treated late in the summer, when daily air and soil temperatures were well below peak maxima. The gypsum wallboard placed over the polyethylene film kept soil temperatures below those of the nontreated control soil. Immediately following treatment, total nematodes were significantly reduced by 86% in the (S) plots, and 43% in the (SH) plots throughout the 0–46 cm sampling depth, compared with the control plots. Nine months later, nematode population densities in the shaded and solarized plots were significantly lower by 59% in the solarized and 48% in the shaded plots, as compared to control plots, in the upper 23 cm of soil only.

Site 10. Several genera of phytoparasitic nematodes were found, including *Helicotylenchus digonicus*, as well as small numbers of *Meloidogyne, Pratylenchus*, and *Xiphinema* spp. Following treatment, total nematodes were significantly reduced (36–81%) by all treatments, as compared to the untreated control throughout the 0–46 cm soil sampling depth. No significant differences were found when population densities of *H. digonicus* or total phytoparasitic nematodes were compared. When soil was assayed for nematode population densities 3 mo later, total nematodes in all treatments, except shaded, remained 54–75% below those in untreated control soil in the 0–23 and overall 0–46 cm depth ranges.

Significant population density reductions (67–98%) were also detected for total phytoparasitic nematodes in the 0–23 cm depth range only for all treatments, as compared to control soil. In addition, significant reductions (68–98%) of population densities of *Helicotylenchus digonicus* were observed in the 0–23 cm depth range in soil from all treatments, and from all treatments except shaded (67–97%) in the overall 0–46 cm depth range, as compared to the control soil. Reductions in population densities of *H. digonicus* were not observed when soil was assayed immediately following treatment 3 mo earlier.

Pepper fruits and vegetative growth of plants transplanted 1 wk after treatment were harvested 2.5–3.0 mo later. All of the treatments, except (T) resulted in increased fresh and dry yields (51–130%) of cultivar Early Jalapeno pods, as compared to the control. All treatments, except (T) and (SH), likewise resulted in increased (82–152%) vegetative growth fresh weights. Soil solarization did not increase fresh pod yield of cultivar Pimiento L on a per-plant basis, although plant survival (34%), vegetative growth fresh weight (32%) and fresh pod yield on a kilograms per hectare basis (64%), was increased over the control treatment. Increased per-plant pod fresh weights of 33% and 40% were found following treatments combining 1,3-D and polyethylene film and 40% in (SH) respectively. Pod yield results with cultivar Resistant Giant were similar to those from cultivar Pimiento L while other measured growth parameters were not significantly different between treatments. Field plant growth data are shown, in part, in Table 4.

Nematode population density data from all field experiments (except site 8) are summarized in Table 5.

DISCUSSION

Population densities of free-living and phytoparasitic nematodes, including *Meloidogyne, Heterodera, Pratylenchus, Paratrichodorus, Criconemella, Helicotylenchus, Xiphinema*, and *Paratylenchus* spp., were significantly reduced by soil solarization, and solarization plus fumigation with 1,3-D, at all experimental sites except one in the coastal Sonoma Valley (Healdsburg). The extent of reduction depended on many factors, including the degree of solar heating, crop and cropping history, nematode taxa

involved, nematode distribution in the soil, and soil depth. No conclusions could be made about the effect of soil type on nematode population reductions. In experiments where nematodes were assayed several months after treatment, population density reductions in solarized plots were often greater than when assayed immediately after treatment, except where solarization treatments were done around existing orchard trees. Therefore, some residual effects lethal to nematodes are evident following soil solarization. These residual effects may be related to the fact that reductions in nematode population densities occurred down to 91 cm depth. Direct heating may not have been as important here as other effects such as possible induced biological control or accumulated volatiles.

Significant yield increases in greenhouse- and field-grown plants usually occurred in soil treated by solarization or 1,3-D plus film covering, heated or not; but not in soil treated with 1,3-D alone, by our application methods. Growth increases following soil solarization were consistent with those reported previously (7,9,10,18,20). No significant increased growth responses were observed in orchard trees when surrounding soil was solarized and/or treated with 1,3-D. Growth data was monitored for only 1 yr following treatment, however, which may be insufficient for measuring growth effects on perennial plants.

Previous studies have shown both low (7,19) and high (17) rates of phytoparasitic nematode recolonization after soil solarization. Although no comprehensive data was obtained for the relative soil recolonizing abilities of the various nematodes encountered in this study, one genus stood out from the rest. *Paratylenchus* spp. consistently recolonized solarized soil very quickly, often to levels much higher than in control soil, especially in existing orchard sites. No definitive data were obtained during these experiments to indicate which phytoparasitic nematodes, if any, were most susceptible to soil solarization, due to the diversity of nematode genera and test conditions at the various sites.

In the two experiments utilizing treatments of moist, plastic-covered but shaded, soil, decreases in nematode population densities were approximately half those obtained in the soil solarization treatments. This indicated that a significant part of the nematicidal effect of soil solarization may be directly or indirectly due to maintaining a high soil moisture content for several weeks, changes in soil gas composition, and/or accumulated volatiles. These findings are consistent with population density comparisons of other soilborne microorganisms between solarized and plastic-covered, but shaded, soils (22).

In the field experiments, soil treatment with partial or full label-recommended doses of 1,3-D by our application methods did not reduce nematode population densities as much as solarization. Covering 1,3-D-treated soil with plastic film, with or without solar heating, however, usually increased the control of nematodes over solarization alone or 1,3-D alone. No information was obtained that would suggest significant synergistic action when solarization and fumigant were combined. Other studies have shown that the nematicidal efficacy of 1,3-D was increased when treated soil was covered by paper (1) or plastic film (3). The application of large volumes of water to soil is necessary for the optimum effect of soil solarization. However, the efficacy of 1,3-D in very moist soil is probably decreased. The effect of irrigation following fumigation with 1,3-D has been studied (24). That practice was found to result in leaching of the fumigant down from the placement zone, increasing the depth of control, but reducing nematode control near the soil surface. Since maximal reduction of nematode population densities following solarization was usually near the soil surface, some downward movement of an added fumigant might be beneficial to the efficacy of the combined treatments.

Whether or not soil solarization alone is a cost-effective method of eliminating nematodes from soil was not determined. A successful nematicide should theoretically eradicate nematodes, especially for perennial crops, and soil solarization did not accomplish this. The benefit to plant health and growth gained by partial reduction of phytoparasitic nematodes in soil likewise was not determined; correlation coefficients between reduction of nematodes and plant growth in the field were not significant for any of these experiments. The data from existing orchard sites were not indicative of satisfactory postplant nematode control, possibly due to protection afforded to nematodes by living roots in the soil during solarization. Solarization as a postplant treatment has been shown to be effective against Verticillium wilt in pistachio groves, however (2). Although control of phytoparasitic nematodes was satisfactory near the soil surface, population density reductions decreased with increasing soil depth. These findings are consistent with others employing hot water treatment of soil to eliminate phytoparasitic nematodes (4,15). Previous studies (7,19) have reported effective control of specific nematodes by soil solarization throughout crop growing seasons, while others (10,17) have reported ineffective control. This study, while not including any field experiments where plant-parasitic nematodes were likely to be the limiting factor of plant growth, resulted in examples of both good and poor nematode control. Therefore, increases of plant growth reported after solarization cannot be attributed solely to reduction of nematode numbers. Additional data is needed on specific crop/nematode interactions to define the limits and extent of control in the field.

The use of 1,3-D with solarization significantly increased the degree of nematode control in some experiments. In addition, increased plant growth responses were usually numerically greatest when the two treatments were combined. Due to the relatively high cost of treating soil by solarization plus a nematicidal chemical, studies on the cost effectiveness of these treatments are needed with adaptable cropping systems. Soil solarization, with or without an added fumigant, would especially lend itself to several cropping situations. Treatment during a summer fallow prior to fall planting; of shallow soils or prior to shallow-rooted crops; where phytoparasitic nematodes (eg, cyst nematodes) are not deeply distributed in soil; or where control of a wide range of pathogens and/or pests is desired (fungi, bacteria, nematodes, soilborne insects, and weed seeds), may prove to be economically advantageous where climatically applicable.

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