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Effect of Combining Soil Solarization with Certain Nematicides on Target and Nontarget Organisms and Plant Growth[1]

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Abstract: Field experiments compared pesticidal and plant growth effects of soil solarization, alone and in combination, with overall applications of several nematicides. Nematodes, including *Meloidogyne incognita* J2, that were targeted for control were significantly reduced ($P < 0.05$) by solarization, 1,3-dichloropropene (44 and 132 liter/ha), ethoprop (13.5 kg/ha), metham sodium (64 liter/ha), formaldehyde (111 liter/ha), and by solarization–nematicide combinations. Control of *Pythium ultimum* also was obtained by all of the treatments; however, none of the chemicals or combinations of chemicals and solarization controlled nematodes or *P. ultimum* significantly better than solarization alone. Numbers of cotton (*Gossypium hirsutum* cv. Acala SJ-2) seed-applied *Trichoderma viride* and *Bacillus subtilis* which colonized the plant rhizosphere were not affected. Yield of carrot and survival of cotton seedlings was sometimes increased by solarization and (or) chemical treatments. No significant phytotoxicity from soil treatments was found on cotton or carrot.

Key words: *Bacillus subtilis*, biological control, chemical control, *Criconemella xenoplax*, *Daucus carota*, 1,3-dichloropropene, ethoprop, formaldehyde, *Gossypium hirsutum*, *Meloidogyne incognita*, metham sodium, *Pythium ultimum*, ring nematode, solarization, southern root-knot nematode, *Trichoderma viride*.

Soil solarization (SS) is a unique method of mulching that integrates pest control, soil and water conservation, and increased growth response of crops (29). The hydrothermal SS process causes complex changes in soil that are deleterious to many plant pests and pathogens while stimulating activity of soil biota beneficial to crop growth (29). Reported efficacy of SS as a nematicidal treatment ranges from excellent to incomplete or inconclusive (2,6,8,13–15,17,18,21–23,25,27).

Because SS is not effective against all target organisms and is somewhat climate limited (29), it has been tested in combination with soil-applied pesticides to control phytonematodes and other soilborne pathogens. Increased control of pests with these combinations has not been consistently shown; some reports indicate that additive or synergistic effects have been obtained (3,10,18,27), whereas others indicate that no additional pest control resulted from adding chemicals to the SS process (12,20,27,30,31). Additional control depends upon the properties and specificity of the product used, as well as other physical, chemical, and biological aspects of the ecosystem (1,24,32).

A primary mode of action of SS involves stimulation of beneficial organisms responsible for residual biological control of phytopathogens and pests (29). Soil and root densities of beneficial fungi and bacteria sometimes increase after solarization (9,28). Addition of pesticides may enhance or diminish the activity of beneficial organisms, thus influencing the overall effect of the treatment.

The experiments described here were designed to compare the field effects of SS, alone and in combination with nematicides, on nematodes including *Meloidogyne incognita* (Kofoid & White) Chitwood and *Criconemella xenoplax* (Raski) Luc & Raski and on *Pythium ultimum* Trow. Residual effects of treatments on beneficial soil and root micro-organisms were determined by

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[1] 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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survival of cotton seedlings and population densities of seed-applied *Trichoderma viride* Pers. ex S. F. Gray and *Bacillus subtilis* (Ehrenberg) Cohn on cotton roots. Yields of carrot also were used to estimate crop growth response.

Materials and Methods

Two field plots at Davis, California, with different soil type and cropping history were used. One plot was on Reiff fine sandy loam soil (0–2% slope; 66% sand, 23% silt, 11% clay; 1% organic matter; pH 7.4). The other was on Reiff silty clay loam (0–2% slope; 20% sand, 44% silt, 36% clay; 1% organic matter; pH 7.0). The first site had been continuously cropped for several years to tomato, and 2 weeks before treatment application contained an aggregated, natural population of 7.0×10^2–3.4×10^4 J2 of *M. incognita* per liter soil and ca. 50 colony-forming units (cfu)/g soil of *P. ultimum*. The second site was cropped to a grapevine nursery-fallow rotation and was fallow for 2 years before these experiments. It contained 0–85 *C. xenoplax*/liter soil, along with 100–200 cfu of *P. ultimum*/g soil. Sites were rototilled to ca. 15 cm deep before treatment. Pretreatment soil temperature was 27 C, and soil moisture was ca. 9% (site 1) or 12% (site 2) at 23 cm deep.

Nematicidal chemicals tested included 1,3-dichloropropene (1,3-D; 44 and 132 liter/ha [4.4 and 13.2 ml/m^2]), ethoprop 10G (13.5 kg/ha [1.35 g/m^2]), formaldehyde (111 liter/ha [11.1 ml/m^2]), and metham sodium (64 liter/ha [6.4 ml/m^2]). Application of 1,3-D was made by Maclean (Neil A. Maclean Co., San Francisco, California—no longer available) hand injector 20 cm deep and sealed by foot pressure; metham sodium and formaldehyde were applied in 18.9 liters of water per replication as surface drenches with buckets, and ethoprop was surface-applied by a drop-type fertilizer spreader and incorporated by light hand raking.

Immediately after pesticide application, field plots were sprinkler irrigated with ca. 4 cm water to bring soil moisture to above field capacity to a depth of ca. 23 cm. Soil below 23 cm deep was at ca. 75% field capacity before irrigation. One day after irrigation, transparent, high-density 1.5-mil polyethylene fumigation film was randomly applied to half of the plots. The plots were either 2 × 2 or 2.3 × 3 m, and six replications of each treatment were used in a completely randomized design. Plots of different size were used because of a limitation on the area of soil infested with *M. incognita*. Maximum-reading thermometers were buried 15 cm deep in a solarized and a noncovered control replication. The plastic mulch remained in place for 21 or 24 days in June–July. The shorter SS period was used along with low chemical dosages in order to more easily detect possible additive or synergistic control interactions. The plots were sprinkler irrigated with ca. 2.5 cm water 1 day before film removal to roughly equalize the moisture contents of the covered and noncovered plots. One week after film removal, the soil was sampled to determine population densities of soil nematodes and fungi. Three soil cores (46 cm deep) per replication were taken randomly with a 2.5-cm-d soil tube and composited. The soil was stored at 10 C, and nemas were extracted from a 300-cm^3 aliquot using a semi-automatic elutriator and centrifugal flotation (16). *P. ultimum* was assayed in air-dried soil according to the method of DeVay et al. (7).

After sampling, the undisturbed plots were rototilled to a depth of ca. 23 cm. Carrot (*Daucus carota* L. cv. Pak Mor F1) seed were planted 2 weeks later. Weeds were controlled both mechanically and by one spray application of grade 2 kerosene at the rate of 350 liter/ha. Carrots were fertilized by one side-dress application of ammonium sulfate (53 kg N/ha) 7 weeks after planting. The crop was rated for stand, fresh weight, and disease symptoms.

To assay for residual effects of the soil treatments, cotton (*Gossypium hirsutum* L. cv. Acala SJ-2) seeds were encapsulated with a mixture of pyrophyllite clay and sodium alginate, alone or amended with the beneficial fungus *T. viride* (strain T-1-R9, ob-

TABLE 1. Effect of soil solarization (SS) and (or) nematicides on soilborne nematodes, *Pythium ultimum* and on yield of carrot (*Daucus carota* cv. Pak-Mor F1).

Treatment and dosage (overall, active ingredient)	Soil type: Fine sandy loam soil — Total nematodes†	*Meloidogyne incognita*†‡	*Pythium ultimum*§	Carrot yield‖	Silty clay loam soil — Total nematodes	*Pythium ultimum*	Carrot yield
1,3-D (132 liter/ha)	2.53 (505)	1.94 (390)	43	3.7	35	69	4.3
1,3-D + SS	1.68 (130)	1.59 (110)	2	4.2	40	15	4.5
1,3-D (44 liter/ha)	2.79 (885)	2.59 (785)	44	4.6	75	70	4.4
1,3-D + SS	1.95 (190)	1.93 (175)	2	5.1	20	15	4.9
Ethoprop (13.5 kg/ha)	2.20 (495)	1.83 (320)	64	4.9	60	52	4.0
Ethoprop + SS	1.91 (225)	1.39 (180)	8	4.4	15	14	4.5
Formaldehyde (111 liter/ha)	2.70 (585)	2.61 (400)	29	5.0	20	54	3.8
Formaldehyde + SS	2.70 (915)	2.59 (760)	5	5.8	15	12	4.9
Metham sodium (64 liter/ha)	2.30 (345)	2.09 (225)	4	5.0	15	8	4.5
Metham sodium + SS	2.21 (725)	2.01 (680)	0	5.6	40	3	4.8
Control	2.98 (1,385)	2.82 (1,160)	55	4.5	110	128	3.7
SS	2.07 (175)	1.97 (160)	5	6.0	35	7	4.5
LSD	0.77	0.97	28.7	1.9	54.5	32.2	1.0
Factorial analysis of variance							
Chemicals	NS¶	0.05	0.05	NS	NS	0.01	NS
Solarization	0.01	0.05	0.01	NS	NS	0.01	0.01
Chemicals–solarization#	NS	NS	NS	NS	NS	0.01	NS

† Log number of nematodes/300 cm^3 soil. Actual nematode counts are given in parentheses.
‡ Number of J2/300 cm^3 soil.
§ Number of colony-forming units/g air-dried soil.
‖ Kg carrot roots/3.05 row m.
¶ Significance level. NS = no significant difference.
# Treatment interaction.

tained from G. Papavizas, USDA ARS, Beltsville, Maryland), or the bacterium *B. subtilis* ('Quantum 4000'—Gustafson, Inc., Plano, Texas) as described by Garber et al. (11). Fungi were applied at a rate of ca. 1.3×10^4 cfu/seed; bacteria were applied at ca. 6.5×10^4 cfu/seed. Ten encapsulated seeds of each seed treatment were planted into each replication of both field plots 2 months after soil treatment. Cultural practices were the same as those described for carrot, except weed control was mechanical. Cotton plants were dug up 2 months after planting and rated for survival and root populations of *T. viride* and *B. subtilis* by removing the soil from the root systems and macerating taproots in 5 ml sterile water, followed by dilution-plating. Acidified potato dextrose agar (26) was used to enumerate *T. viride,* and 523 agar amended for selectivity for *Bacillus* spp. (26) was used to recover *B. subtilis.*

RESULTS

Maximum temperatures at 15 cm deep in the solarized and noncovered plots were 47 C and 36 C, respectively, in the fine sandy loam soil, and 44 C and 36 C, respectively, in the silty clay loam soil. Air temperature recorded by the National Oceanic and Atmospheric Administration Climatological Station at Davis, California, was 33 C (mean max.) and 13 C (mean min.) at 2 m altitude during the soil treatment period.

Experimental parameters from each nematicide and nematicide–solarization combination were compared with those from SS and nonsolarized control treatments using a factorial analysis of variance (19). Nematode data from the fine sandy loam plot were log-transformed before analysis due to aggregated *M. incognita* populations (19). The total number of parasitic and free-

TABLE 2. Effect of soil solarizaiton (SS), nematicides, and microbial seed treatments on survival percentage of cotton (*Gossypium hirsutum* cv. Acala SJ-2).

Treatment and dosage (overall, active ingredient)	Survival percentage					
	Fine sandy loam soil Seed treatment†‡			Silty clay loam soil Seed treatment		
	Trichoderma viride	*Bacillus subtilis*	Carrier only	*Trichoderma viride*	*Bacillus subtilis*	Carrier only
1,3-D (132 liter/ha)	16	8	3	30	52	35
1,3-D + SS	27	30	40	50	27	18
1,3-D (44 liter/ha)	20	15	17	53	28	17
1,3-D + SS	58	48	48	40	58	43
Ethoprop (13.5 kg/ha)	13	13	15	33	20	18
Ethoprop + SS	38	22	23	33	52	12
Formaldehyde (111 liter/ha)	8	12	8	38	20	15
Formaldehyde + SS	43	48	35	37	45	62
Metham sodium (64 liter/ha)	37	47	40	43	42	28
Metham sodium + SS	45	32	37	50	33	32
Control	10	21	5	35	40	38
SS	18	33	57	45	47	30
LSD		26.9			31.8	
Factorial analysis of variance						
Chemicals		0.01§			NS	
Solarization		0.01			0.05	
Seed treatments		NS			0.05	
Chemicals–seed treatments‖		0.01			NS	
Solarization–seed treatments‖		NS			NS	
Chemicals–seed treatments‖		NS			NS	
Chemicals–solarization–seed treatments‖		NS			NS	

† Treatments applied 2 months prior to planting of seed.
‡ *T. viride* (#T-1-R9) obtained from G. Papavizas, USDA ARS, Beltsville, Maryland, and *B. subtilis* ('Quantum 4000'—Gustafson, Inc., Plano, Texas) applied to seed in pyrophillite clay–sodium alginate carrier.
§ Level of significance. NS = no significant difference.
‖ Treatment interaction.

living vermiform nematodes were significantly reduced by SS, by ethoprop with and without SS, and by both dosages of 1,3-D + SS. Numbers of *M. incognita* were reduced by ethoprop with and without SS and by 1,3-D (132 liter/ha) + SS. In the silty clay loam soil total vermiform nematodes were significantly reduced by SS, 1,3-D (132 liter/ha), formaldehyde, metham sodium, and all chemical treatments + SS. No treatment interaction between SS and chemicals was found (Table 1).

Posttreatment assays of *P. ultimum* in fine sandy loam soil showed that statistically significant population reductions occurred after treatment with SS, metham sodium, and SS + all chemical treatments. No significant additive or synergistic interactions occurred between SS and any of the nematicides. In the silty clay loam soil, *P. ultimum* was significantly reduced by all of the treatments relative to the nontreated control (Table 1). A significant negative interaction was found when SS and chemicals were combined.

Carrot yield in the fine sandy loam soil was not affected by any of the soil treatments (Table 1). No differences in stand were found, and the incidence of root galling and forking was insignificant. At the silty clay loam site, increases in yield occurred in soil treated with combinations of SS + 1,3-D (44 liter/ha), formaldehyde, and metham sodium. Overall yield means in solarized plots were significantly greater ($P < 0.01$) than in those without SS.

Cotton survival in the fine sandy loam site was affected by soil treatments but not

by seed treatments (Table 2). Seedling survival was increased by SS and chemicals ($P < 0.01$), regardless of seed treatment. A significant positive interaction between SS and chemicals was found. *Trichoderma viride*-treated seedlings survived best in soil treated with metham sodium and with combinations of 1,3-D (44 liter/ha), ethoprop, formaldehyde, and metham sodium + SS. Seedlings from *B. subtilis*-treated seed survived best in soil treated with combinations of 1.3-D (44 liter/ha) and formaldehyde + SS. Seedling survival in the silty clay loam site was affected by SS and by seed treatment (Table 2).

Discussion

SS is a treatment whose pesticidal and crop growth-promoting effects are dependent upon the ecosystem in which it is used. Differences in climate and weather, soil type and properties, nature of target and nontarget organisms, and other variables all affect the performance of the soil treatment and the subsequent crop. When pesticides are added to SS, with inherent high soil temperature and moisture levels, they may or may not enter into an environment which is conducive to pesticidal activity and rapid dissipation. For example, metham sodium requires water to form the active ingredient, methyl isothiocyanate (10), whereas moist soil causes the fumigant 1,3-D to hydrolyze into the less volatile, phytotoxic derivative 3-chloroallyl alcohol (5). For this reason, the efficacy of SS for pest control and yield increase cannot be generalized, even when used in combination with a chemical.

The application of 4 cm water to the soil surface after pesticides were applied undoubtedly affected the diffusion dynamics and pesticidal efficacy of the chemicals. The effect of driving pesticides deeper into soil when used with SS has been discussed (27). Since the effects of SS are often greatest near the soil surface, it was proposed that increased downward movement of chemicals may be beneficial to the combined treatments. The present study was designed to determine the effects of combining chemical pesticides with SS, which requires high soil moisture content, rather than to evaluate pesticides against each other. Partial and full-label dosages of 1,3-D were used in this study because a previous study (27) suggested that some 1,3-D/SS combinations were phytotoxic. No significant phytotoxic effects were found during these experiments.

Previous reports on combining biological control organisms with SS (9,28) suggest that colonization of soil and roots by fungal and bacterial antagonists is facilitated by SS. In this study, however, significant differences in root population densities of *T. viride* and *B. subtilis* were undetectable between treatments. Large population variances between individual plants contributed to the lack of statistical significance.

SS as a method treatment for disinfesting soil and increasing crop growth often is most effective without pesticidal amendments (12,20,27,30,31). Significant additive or synergistic interactions between SS and chemical soil pesticides are not routinely encountered. The results of this study, showing generally greater control of nontarget *P. ultimum* than of nematode populations by all SS–nematicide combinations, suggest that these interactions may occur more often with fungal pathogens. The combination of SS and chemical soil treatments has given excellent control of some pests which otherwise would not be controlled and may offer pest control with a less-than-label dosage of a pesticide. For these reasons, additional work is warranted in order to extend and define the effects of combining chemical pesticides with soil solarization.

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