Effect of Chicken Compost or Ammonium Phosphate and Solarization on Pathogen Control, Rhizosphere Microorganisms, and Lettuce Growth

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ABSTRACT

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Two field experiments were conducted to determine effects of commercial chicken compost, ammonium phosphate fertilizer, and solarization, alone or combined, on several soilborne pathogens and the growth and yield of lettuce (*Lactuca sativa*). Southern root-knot nematode (*Meloidogyne incognita*) present at one of the sites was effectively controlled by the combination of these treatments, whereas solarization alone gave only partial control. *Pythium ultimum* was controlled by both solarization alone and combined with chicken compost. Lettuce yield was significantly increased by most solarization treatments in successive fall and spring crops at both locations. However, an inhibitory effect on lettuce growth and yield in the fall crop was observed in the plots that were amended with compost after solarization. The rhizosphere of lettuce plants grown on solarized soils was intensively colonized by fluorescent pseudomonads and *Bacillus* spp. Numbers of *P. ultimum* and other fungi were suppressed in solarized plots during the two successive lettuce crops.

Additional keywords: biological control

Under suitable climatic conditions, soil solarization can be an effective method of controlling a broad spectrum of fungi, nematodes, weeds, and other plant pests in diverse agricultural systems, including in field and greenhouse production and in container media (2,14,16). Nevertheless, some soilborne pests such as root-knot nematodes (*Meloidogyne* spp.) are not always controlled effectively by solarization (25,26). Solarization frequently results in improved plant growth and yield increase (3,7,8,22–24) and in induced suppressiveness against reestablishment of major and minor fungal pathogens in treated soil (9,11,14). These effects can be partially attributed to increased populations of beneficial fungi and bacteria in the rhizosphere and roots of plants grown in solarized soils (3,8,9,23,26).

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Addition of fertilizers and organic amendments, especially composts, can suppress soilborne plant pests in various cropping systems (4,5,12). The suppressive effect is attributed to shifts in microbial populations and activity in soil following the addition of the organic material (4,12). Antagonists of plant pathogens have been isolated from organic composts (5). Inorganic fertilizers containing ammoniacal nitrogen or formulations releasing ammonia from nitrogen in soil also have been effective in suppressing nematode populations when applied at high rates (17). Limited data are available on the effect of solarization of compost or fertilizer-amended soil on improved control of certain plant pathogens and weeds (2,16,24). The purpose of this study was to determine the effects of soil amendment with chicken compost or inorganic ammonium phosphate fertilizer, with and without soil heating, on pathogen control, microbial populations in soil and rhizosphere, and lettuce growth and yield.

MATERIALS AND METHODS

Field sites. Two field experiments were conducted in the San Joaquin Valley during 1991–1992. One was on Hanford sandy loam soil at the University of California Kearney Agricultural Center (KAC) near Parlier, where grapes were previously grown. The soil is infested with southern root-knot nematode (*M. incognita* (Kofoid & White) Chitwood) and *Pythium ultimum* Trow. The second location was on Panoche sandy clay soil at the University of California West Side Field Station (WSFS) near Five Points. The plot was previously cropped with garlic and other vegetables and was not known to contain major plant pathogens other than *P. ultimum*.

Experimental design and soil treatment. Factorially designed experiments were done at both KAC and WSFS. Plots were arranged in a randomized block design with five replications per treatment, each of four adjacent beds 16 m long × 4 m wide. Commercially formulated chicken compost (2.15% N, 0.3% P, 1.7% K, at a rate of 10 t/ha; Foster Farms, Livingston, CA) or commercial ammonium phosphate fertilizer (16% N, 20% P_2O_5 at a rate of 500 kg/ha, which was equivalent to the total nitrogen content in the chicken compost; J. R. Simplot, Helm, CA) was manually spread on the plots, then incorporated into the soil by rototilling. Solarization of compost- or fertilizer-amended plots was done by mulching soil with 0.013-mm-thick clear polyethylene sheets. Each experiment was mulched for a period of 4 wk during August 1991. Soil temperature data were continuously collected with a micrologger (CR-21X, Campbell Scientific, Logan, UT). Post-solarization fertilizer treatments included incorporation of compost or ammonium phosphate at the same rates 7 days before planting. Controls were plots with no compost, fertilizer, or solarization. Beds (1 m wide) were shaped following incorporation of the postsolarization amendments.

Cultural practices. Two successive crops of leaf lettuce (*Lactuca sativa* L. 'Parris Island Cos') were grown in both fields. The first crop was planted in mid-September 1991, sprinkle-irrigated, and farmed according to the University of California recommendation for central California (27). Sidedress fertilization of ammonium phosphate at a rate of 500 kg/ha was applied to all treatments after thinning (1 mo after planting). Plots were harvested in December 1991, and the beds were left undisturbed during the winter. A spring crop of leaf lettuce was planted in both fields on the same beds in February 1992 and farmed as the first crop.

Measurements of plant growth, yield, and disease severity. Stand counts were made before thinning in each crop in order to determine possible effect of soil treatments on seedling emergence. Fresh weight of lettuce plants was determined at 4 and 7 wk and at harvest. Galling of roots by *M. incognita* was assessed after 4 wk and at harvest at the KAC experiment. This was done by subjectively rating plants for percentage of the total volume of roots with galling, where 0 = roots with no galls and 100% = galling of the entire root system.

Greenhouse experiment. In order to estimate numbers of infective *M. incognita* individuals at KAC during the spring lettuce crop, soil samples were taken from each replication and placed in two 15-cm-diameter pots. Tomato (*Lycopersicon esculentum* Mill. 'Cherry Belle') transplants were planted in each pot and grown in a greenhouse for 6 wk, at which time plants were removed from the pots and the extent of root galling was determined as in the field.

Microbial colonization of the rhizosphere. Lettuce plants were uprooted along with adherent soil several times during the growing season. Loose soil clinging to roots was collected by shaking the plants in sterile tubes; soil adhering to roots (less than 5% of the total amount of rhizosphere soil) was collected by shaking the plants in sterile water agar (1 mg/ml) supplemented with 1 mg/ml of $MgSO_4 \cdot 7H_2O$. Both soil fractions were combined to constitute the rhizosphere soil sample. Rhizosphere soil suspensions were serially diluted, and 0.1-ml samples for bacterial counts and 0.2-ml samples for fungal counts were spread on five petri dishes containing the appropriate selective medium. Dishes were incubated in the dark at 28 C. Colonies were counted after 4–8 days. Results were expressed as colony-forming units per gram of soil (dried at 105 C for 48 hr).

Culture media. For enumeration of fluorescent pseudomonads from soil and rhizosphere, King's medium B (KB) modified by the addition of 100 mg/L of cycloheximide, 50 mg/L of ampicillin, and 12.5 mg/L of chloramphenicol (19–21) and supplemented with 5 mg/L of pentachloronitrobenzene (PCNB) to suppress *Rhizopus* spp. (7) was used. Martin's agar (6) was used for enumeration of fungi, and Mircetich's agar (15) was used for enumeration of *P. ultimum*. For enumeration of *Bacillus* spp., 523 agar (13) modified by the addition of 32 mg/L of polymyxin B sulfate, 2 mg/L of sodium azide, and 250 mg/L of cycloheximide (26) and supplemented with 5 mg/L of PCNB was used.

Statistical analyses. Data were first analyzed by analysis of variance to test possible interaction among the main effects, followed by mean separation using Fisher's protected least significance difference test. Regression analysis was conducted to test correlation between nematode infection and lettuce yield in the fall crop at KAC. Data taken as percentage were arcsine-transformed prior to analysis. All analyses were performed with the SAS program (SAS Institute, Cary, NC, release 6.04 for personal computer) at $P \leq 0.05$.

RESULTS

Soil temperature. Temperature fluctuation in solarized and nonsolarized plots is shown in Figure 1. Compost amendment to soil before solarization increased soil temperature by approximately 2 C compared with the temperature of nonamended solarized soil. Maximal temperatures at depths of 10 and 20 cm in the compost-amended solarized soil were 52 and 45 C, respectively, compared with 50 and 43 C, respectively, in the nonamended solarized soil. There was no difference in soil temperature between ammonium-phosphate-amended and nonamended solarized treatments or between compost-amended and non-amended nonsolarized plots.

Plant growth and yield. The number of lettuce plants in the solarized plots during the fall crop at KAC was significantly higher than the number in the nonsolarized plots (7.4 and 4.2 plants per meter, respectively). There were no significant differences in the number of plants among soil amendment treatments or times of incorporation. None of the treatments had an effect on plant stand in the fall experiment at WSFS or in the spring crop at either location. Plant

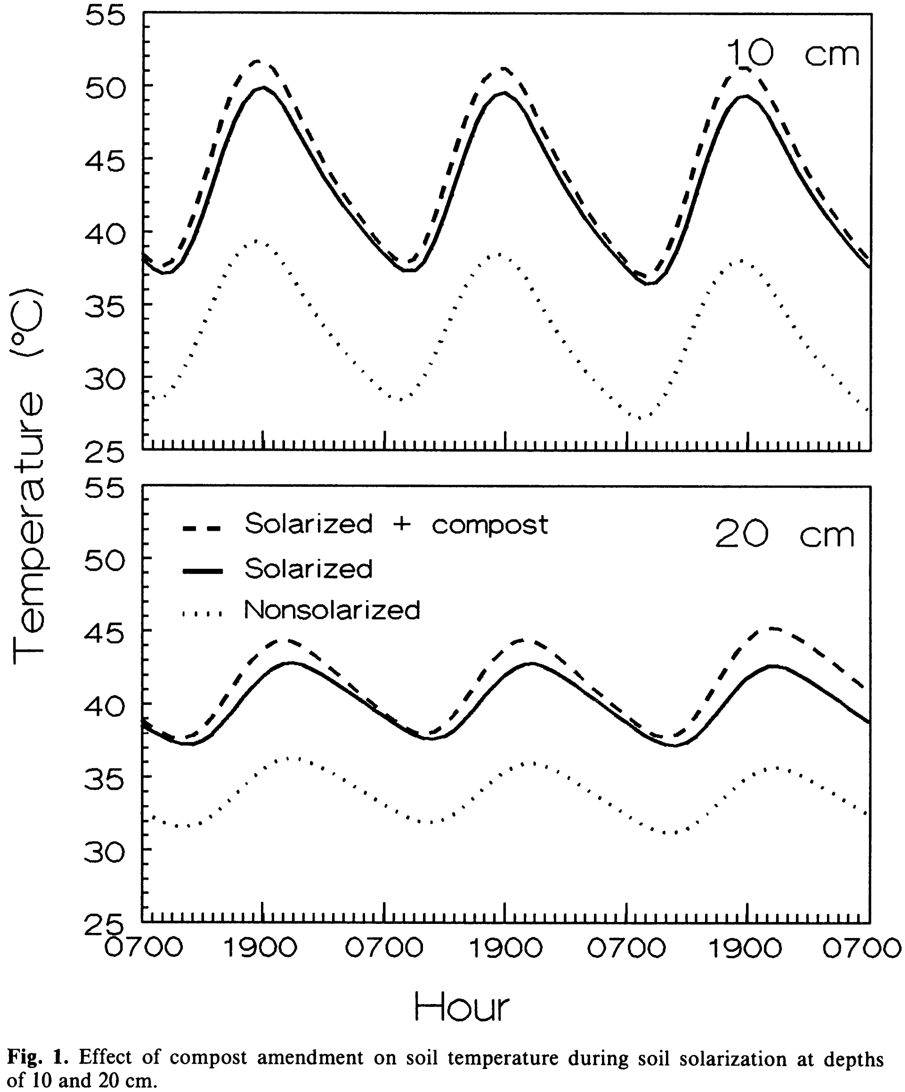

Fig. 1. Effect of compost amendment on soil temperature during soil solarization at depths of 10 and 20 cm.

samples were taken for determination of fresh weight after 4 and 7 wk. Greater fresh weight amounts were recorded from plants grown in the solarized plots than from those grown in nonsolarized plots. In contrast, lower fresh weights were evident in lettuce plants grown in plots with postsolarization amendment of compost (*data not shown*).

Lettuce yield was increased in solarized plots at both locations in fall and spring crops (Table 1). In the fall crop, total yield was increased after solarization by 51 and 12% at KAC and WSFS, respectively. The corresponding yield increase in the spring crop was 93 and 9%, respectively. There was no significant interaction effect of solarization and fertilizer amendments on lettuce yield. Nevertheless, yield of lettuce in the presolarized compost-amended soils was 24 and 26% higher than that in the plots that were solarized without compost treatment at KAC and WSFS, respectively. In contrast, postsolarization compost amendment resulted in reduction in fall yield at both sites. Lettuce yield was reduced in this treatment by 24 and 4% compared with solarization alone at KAC and WSFS, respectively. The negative effect of the postsolarization compost amendment on lettuce yield was not evident in the spring crop in either experiment. Lettuce yields in the ammonium-phosphate-treated plots were not significantly different from those in the corresponding controls (Table 1). Differences in total yield among treatments were similar to those of mean fresh weight of lettuce heads (*data not shown*).

Nematode infection. Root galling caused by *M. incognita* was reduced significantly by solarization and to a lesser extent by soil amendment with compost and ammonium phosphate in the fall crop at KAC (Table 2). Galling was totally eliminated in solarized plots amended with compost during the entire crop season. A significant linear relationship was established between nematode infection and lettuce yield (yield = 12.3 [gall percentage] − 0.36; $r^2 = 0.713$) in the fall crop. However, although nematode infection was very mild in the spring crop, there were still significant differences in yield among treatments. The greenhouse experiment conducted to determine if infective nematodes were present in soil during the spring crop showed low levels of galling in the nonsolarized treatments but not in the solarized treatments.

Rhizosphere colonization. Colony-forming units of *P. ultimum* were effectively reduced by solarization and slightly reduced by fertilizer amendments prior to harvest at both KAC and WSFS. The number of *Pythium* propagules in soil was reduced by solarization below detectable levels compared with 45 and 30 cfu/g of soil in the nonsolarized treatments at KAC and WSFS, respectively. Colonization of lettuce rhizosphere by *P. ultimum* was assayed four times during fall crops and three times during spring crops, and establishment of the fungus was found to be significantly suppressed in solarized plots at both sites (Table 3). Colonization of lettuce rhizosphere by *P. ultimum* during the fall crop was suppressed by 82 and

Table 1. Effect of soil solarization, chicken compost, and ammonium phosphate fertilization on fresh yield of leaf lettuce in two successive crops, 1991–1992[a]

Site / Soil treatment	Fall crop fresh yield (t/ha): No amendment	Fall: Compost Early	Fall: Compost Late	Fall: $(NH_4)_3PO_4$ Early	Fall: $(NH_4)_3PO_4$ Late	Spring crop fresh yield (t/ha): No amendment	Spring: Compost Early	Spring: Compost Late	Spring: $(NH_4)_3PO_4$ Early	Spring: $(NH_4)_3PO_4$ Late
Kearney Agricultural Center										
Nonsolarized	6.6	9.0	6.9	7.0	6.0	9.5	10.0	8.0	8.4	7.8
Solarized	11.0	13.7	8.4	10.6	10.0	13.3	16.0	14.3	13.8	12.1
LSD of main effects ($P = 0.05$)[b]		Fall	Spring							
Solarization		0.55	0.64							
Fertilizer amendment		0.63	0.72							
Time of fertilizer application		0.75	0.93							
West Side Field Station										
Nonsolarized	9.3	10.2	9.8	9.1	9.0	17.9	19.7	19.1	17.3	18.0
Solarized	10.2	12.9	9.8	10.4	10.0	19.7	21.2	19.3	20.1	19.8
LSD of main effects ($P = 0.05$)		Fall	Spring							
Solarization		0.47	0.42							
Fertilizer amendment		0.63	0.53							
Time of fertilizer application		0.51	0.74							

[a]Compost and ammonium phosphate were applied either before solarization (early) or after termination of solarization and before planting (late).

[b]Because there were no significant interactions among the main effects, LSD values are given only for the main effects.

Table 2. Effect of soil solarization, chicken compost, and ammonium phosphate fertilization on root galling of leaf lettuce by *Meloidogyne incognita* at Kearney Agricultural Center 28 and 70 days after planting[a]

Soil treatment	Mean volume of roots galled (%), 28 Days after planting: No amendment	28 d: Compost Early	28 d: Compost Late	28 d: $(NH_4)_3PO_4$ Early	28 d: $(NH_4)_3PO_4$ Late	70 Days after planting: No amendment	70 d: Compost Early	70 d: Compost Late	70 d: $(NH_4)_3PO_4$ Early	70 d: $(NH_4)_3PO_4$ Late
Nonsolarized	30.0	24.0	20.2	19.7	23.0	16.1	12.2	13.0	14.0	18.6
Solarized	4.8	0.0	2.6	4.4	4.1	4.2	0.0	4.8	4.7	4.8
LSD of main effects ($P = 0.05$)[b]		28 days	70 days							
Solarization		5.8	4.2							
Fertilizer amendment		6.4	3.8							
Time of fertilizer application		5.5	4.1							

[a]Compost and ammonium phosphate were applied either before solarization (early) or after termination of solarization and before planting (late).

[b]Because there were no significant interactions among the main effects, LSD values are given only for the main effects. Data were arcsine-transformed for statistical analysis.

100% in the solarized plots compared with the nonsolarized plots at KAC and WSFS, respectively. Suppression of *P. ultimum* remained evident in the spring crop at both locations (Table 3). Plants were uprooted at the KAC experiment at the end of spring crop and assayed for *P. ultimum* infection by root isolation; *P. ultimum* was recovered from 90% of the root segments showing symptoms of rootlet rot.

Numbers of total fungi before planting were significantly reduced in solarized soil by 65–78% compared with numbers in nonsolarized soil at harvest (Table 4). Establishment of fungi in the rhizosphere of lettuce plants grown in solarized soil was suppressed in both KAC and WSFS fields. Results were inconsistent after soil amendment with compost or ammonium phosphate. Suppression of fungal establishment in the rhizosphere of lettuce plants in solarized plots was evident also in the spring crop in both fields, but to a lesser extent than in the fall.

In contrast to the effect of solarization on fungi, numbers of *Bacillus* spp. in soil were not significantly reduced after solarization, and numbers of colony-forming units increased in the rhizosphere of lettuce plants in solarized plots compared with nonsolarized plots when assayed at harvest (Table 5). Numbers of *Bacillus* spp. remained higher in rhizosphere of plants in the solarized plot in the spring crop at both sites. Numbers of fluorescent pseudomonads also were six to 10 times higher in the rhizosphere of lettuce plants in solarized plots than in plants in nonsolarized plots in the fall crop (Table 6). Numbers of these bacteria remained higher in the rhizosphere of plants in solarized soil in the spring crop at both field sites.

Compost or ammonium phosphate fertilizer treatments did not have consistent effect on rhizosphere colonization by microbial groups tested in either fall or spring crops (Tables 3–6).

DISCUSSION

Solarization of compost-amended soil was very effective in controlling *M. incognita* in lettuce at the KAC location.

Table 3. Effect of soil solarization, chicken compost, and ammonium phosphate fertilization on survival of *Pythium ultimum* in the rhizosphere of leaf lettuce at two field locations, 1991–1992[a]

	Colony-forming units per gram oven-dried soil									
	Fall crop					Spring crop				
	No amendment	Compost		$(NH_4)_3PO_4$		No amendment	Compost		$(NH_4)_3PO_4$	
Site / Soil treatment		Early	Late	Early	Late		Early	Late	Early	Late
Kearney Agricultural Center										
Nonsolarized	232	232	155	230	226	800	500	640	600	640
Solarized	46	32	52	53	50	40	20	20	60	40
LSD of main effects ($P = 0.05$)[b]		Fall	Spring							
Solarization		19	50							
Fertilizer amendment		25	53							
Time of fertilizer application		21	49							
West Side Field Station										
Nonsolarized	80	70	66	60	60	640	440	560	540	600
Solarized	0	0	0	0	0	40	20	40	20	20
LSD of main effects ($P = 0.05$)		Fall	Spring							
Solarization		12	49							
Fertilizer amendment		15	62							
Time of fertilizer application		10	57							

[a]Compost and ammonium phosphate were applied either before solarization (early) or after termination of solarization and before planting (late).
[b]Because there were no significant interactions among the main effects, LSD values are given only for the main effects.

Table 4. Effect of soil solarization, chicken compost, and ammonium phosphate fertilization on survival of fungi in the rhizosphere of leaf lettuce at two field locations, 1991–1992[a]

	Colony-forming units per gram oven-dried soil (×1,000)									
	Fall crop					Spring crop				
	No amendment	Compost		$(NH_4)_3PO_4$		No amendment	Compost		$(NH_4)_3PO_4$	
Site / Soil treatment		Early	Late	Early	Late		Early	Late	Early	Late
Kearney Agricultural Center										
Nonsolarized	240	250	210	290	240	850	850	980	960	970
Solarized	72	66	64	50	52	400	450	380	400	410
LSD of main effects ($P = 0.05$)[b]		Fall	Spring							
Solarization		35	58							
Fertilizer amendment		28	72							
Time of fertilizer application		32	48							
West Side Field Station										
Nonsolarized	360	300	320	250	280	440	412	396	474	482
Solarized	60	64	62	84	74	80	94	192	100	110
LSD of main effects ($P = 0.05$)		Fall	Spring							
Solarization		42	52							
Fertilizer amendment		35	43							
Time of fertilizer application		32	39							

[a]Compost and ammonium phosphate were applied either before solarization (early) or after termination of solarization and before planting (late).
[b]Because there were no significant interactions among the main effects, LSD values are given only for the main effects.

Solarization alone or combined with other fertilizer regimes gave only partial control of *M. incognita*, as reported in other studies (25,26). Soil amendment with chicken compost or ammonium phosphate without solarization resulted in slight reduction of root galling by *M. incognita* and of numbers of *P. ultimum*, as previously reported (16,17,24). Temperature of solarized soil amended with compost increased by two to three degrees centigrade, compared with nonamended solarized soil, which may be an important factor for improving control of *M. incognita* and other high-temperature organisms. Possible reasons for the increase in soil temperature are increased soil moisture and thermal conductivity in the compost-amended soil and/or exothermic microbial activity. The improved control of root-knot nematode in solarized soil amended with organic material also may be attributed to increased volatile evolution from the decomposing compost (10,28). Nematode infection was not evident in any treatment in the spring crop at KAC. Soil temperatures during the spring crop were probably too low for nematode activity, as supported by the greenhouse experiment, in which tomato plants grown in soil samples taken from the field became galled in the nonsolarized soil.

Yield of both fall and spring lettuce crops was increased by solarization at both locations. Increase in lettuce yield following solarization was evident in both total fresh yield (Table 1) and mean head weight (*data not shown*). Postsolarization compost treatment had a negative effect on lettuce growth and yield in the fall crop compared with solarization alone at both sites (Table 1). In contrast, other compost treatments showed no negative effects on plant growth. It is possible that postsolarization compost amendment decomposed more slowly in soil because of reduction of nitrifying bacteria and/or release of phytotoxic compounds during the first weeks of crop growth. This

Table 5. Effect of soil solarization, chicken compost, and ammonium phosphate fertilization on survival of *Bacillus* spp. in the rhizosphere of leaf lettuce at two field locations, 1991–1992[a]

	Colony-forming units per gram oven-dried soil (×10,000)									
	Fall crop					Spring crop				
Site	No amendment	Compost		$(NH_4)_3PO_4$		No amendment	Compost		$(NH_4)_3PO_4$	
Soil treatment		Early	Late	Early	Late		Early	Late	Early	Late
Kearney Agricultural Center										
Nonsolarized	70	61	90	98	90	100	136	120	150	140
Solarized	210	200	250	180	200	504	468	480	476	464
LSD of main effects ($P = 0.05$)[b]		Fall	Spring							
Solarization		45	42							
Fertilizer amendment		37	28							
Time of fertilizer application		42	35							
West Side Field Station										
Nonsolarized	296	202	250	122	215	324	288	377	288	356
Solarized	566	578	614	570	636	560	576	636	644	576
LSD of main effects ($P = 0.05$)		Fall	Spring							
Solarization		41	43							
Fertilizer amendment		34	35							
Time of fertilizer application		37	38							

[a]Compost and ammonium phosphate were applied either before solarization (early) or after termination of solarization and before planting (late).
[b]Because there were no significant interactions among the main effects, LSD values are given only for the main effects.

Table 6. Effect of soil solarization, chicken compost, and ammonium phosphate fertilization on survival of fluorescent pseudomonads in the rhizosphere of leaf lettuce at two field locations, 1991–1992[a]

	Colony-forming units per gram oven-dried soil (×10,000)									
	Fall crop					Spring crop				
Site	No amendment	Compost		$(NH_4)_3PO_4$		No amendment	Compost		$(NH_4)_3PO_4$	
Soil treatment		Early	Late	Early	Late		Early	Late	Early	Late
Kearney Agricultural Center										
Nonsolarized	5	12	10	7	8	46	80	93	48	49
Solarized	65	56	57	72	66	110	256	230	150	150
LSD of main effects ($P = 0.05$)[b]		Fall	Spring							
Solarization		3.1	15.2							
Fertilizer amendment		3.3	10.5							
Time of fertilizer application		4.2	12.4							
West Side Field Station										
Nonsolarized	14	12	12	10	10	44	48	54	54	62
Solarized	54	57	61	57	60	116	176	160	185	176
LSD of main effects ($P = 0.05$)		Fall	Spring							
Solarization		4.2	11.4							
Fertilizer amendment		5.1	15.1							
Time of fertilizer application		3.5	11.2							

[a]Compost and ammonium phosphate were applied either before solarization (early) or after termination of solarization and before planting (late).
[b]Because there were no significant interactions among the main effects, LSD values are given only for the main effects.

possibility is supported by the fact that no other compost treatments had adverse effects on lettuce growth. No negative effect of postsolarization composting was observed in the spring crop at either experiment.

Yield of lettuce in the fall crop at KAC was highly correlated with the severity of root galling. However, increased crop yield after solarization was significant at KAC in the spring crop, even when nematode galling did not occur. Other factors, such as root infection by *P. ultimum* and other soilborne pathogens (18), could have been responsible.

P. ultimum extensively colonized the rhizosphere of lettuce plants grown in nonsolarized soil in the fall and, especially, the spring crops. Rootlet injury was evident in plants grown in nonsolarized soil in the spring crop at KAC, and *P. ultimum* was the predominant fungus isolated from those rootlets. This was perhaps due to cold spring soil temperature favoring *P. ultimum* activity following the buildup of populations during the fall crop. Rootlet injury was less evident in the spring crop at WSFS, where lower numbers of *Pythium* propagules in the rhizosphere were recorded (Table 3). Rootlet injury was not evident in either experiment in plants grown in solarized soil.

Numbers of both *Bacillus* spp. and fluorescent pseudomonads were increased in the rhizosphere of lettuce plants in solarized soils during fall and spring crops at the two sites. Populations of *Bacillus* spp. were not reduced during the solarization process as shown previously (26). In contrast, fluorescent pseudomonads that are heat-sensitive and do not survive solarization in high numbers also increased in the rhizosphere of plants in solarized soils in accordance with previous studies (7–9,22). Many species of both bacterial groups are considered to promote plant growth (1,8,19,20). Suppression of major and minor pathogens in solarized soil was related in a previous study to high numbers of fluorescent pseudomonads in the rhizosphere and roots (8). *Bacillus* spp. are also known for antibiotic production (5,23). Increased populations of both fluorescent pseudomonads and *Bacillus* spp. in the rhizosphere of plants grown in solarized soil might be an important factor in the suppression of pathogens and increased yield, as shown in previous studies (5,8,9,23). The direct interaction between these bacteria and pathogens was not tested in this study.

Combination of compost amendment and solarization was very effective in controlling *M. incognita* and *P. ultimum* and resulted in significantly improved lettuce yield in two consecutive crops. The use of available organic amendments such as composts, plant residues, green manures, and fertilizers may be an effective, nonchemical way to improve pesticidal efficacy when solarization alone cannot provide adequate control of target pathogens. Further studies will be required to explore the wide range of possibilities.

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