Effect of Soil Solarization and Cover Crops on Populations of Selected Soilborne Plant Pathogens in Western Oregon

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ABSTRACT

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Field experiments were conducted in silty-clay loam in Corvallis, OR during the summers of 1995 and 1996 to study the effects of green manure cover crops (Sudan grass, rape, and barley), soil solarization, soil fumigation, and combinations of those treatments on population densities of soil pathogens *Verticillium dahliae*, *Phytophthora cinnamomi*, *Pratylenchus penetrans*, and *Agrobacterium rhizogenes*. Nylon mesh bags containing soil infested with *V. dahliae* and *Phytophthora cinnamomi* were buried 5, 10, 20, and 30 cm deep. Soil solarization was performed over a 54- to 59-day period using a 0.6-mil clear polyethylene film. Maximum soil temperatures recorded at depths of 5, 10, 20, and 30 cm were 53, 48, 39, and 34°C in solarized soil, respectively; these temperatures were 8 to 16°C higher than in corresponding nonsolarized plots. Soil samples were collected before, during, and after solarization to quantify pathogen populations at those four depths. Pot or field studies were conducted subsequent to treatments to determine the effects of treatments on susceptible plants. Soil solarization, cover crops plus solarization, or fumigation with metam sodium resulted in a significant decrease ($P < 0.05$) in density of *P. cinnamomi* populations at all four depths and reduced ($P < 0.05$) *V. dahliae* at 5 and 10 cm. In greenhouse assays of solarized soils, disease severity was reduced ($P < 0.05$) for *Verticillium* spp. on eggplant and *Phytophthora* spp. on snapdragons. Cover crops alone were not effective in reducing *P. cinnamomi* and *V. dahliae* populations. *Agrobacterium* spp. population densities declined within solarized plots and incidence of crown gall on 'Mazzard' cherry rootstock planted in solarized plots was reduced significantly. Population densities of *Pratylenchus penetrans* were reduced in the upper 30-cm soil profile by solarization. Solarization for an 8-week period during the warmest months of summer could provide an additional management alternative for several important soilborne pathogens in western Oregon.

Additional keywords: green manure, metam sodium, methyl bromide, root-lesion nematode, soil amendment

Due to the environmental hazards associated with soil fumigation by methyl bromide, a search for alternative methods of controlling soilborne pathogens has become a priority of the United States Department of Agriculture-Agricultural Research Service (USDA-ARS). A ban on the manufacture and importation of methyl bromide in the United States will be effective in 2005 due to concerns about its role in ozone depletion (9). This limitation leaves the agricultural industry in a transi-

tional situation, searching for other management tools. Therefore, the effects of alternative practices, such as cover cropping, soil solarization, applications of metam sodium, and combinations of these methods, need to be evaluated on populations of plant pathogens and disease incidence.

Soil solarization, the process of heating soils under transparent plastic tarps to temperatures detrimental to soilborne pathogens, has successfully controlled a variety of plant diseases (42). Solarization is a novel approach because it targets mesophilic organisms, which include most plant pathogens and pests, without destroying the beneficial mycorrhizal fungi and growth-promoting *Bacillus* spp. (39,41). Increased soil temperatures result in decreased populations of weeds (19) and a range of plant pathogens, including fungi (18), bacteria (35), and nematodes (43). If not directly inactivated by heat, soilborne plant pathogens may be weakened (13) and become vulnerable to soil fumigants, to other organisms, or to changes in the soil atmosphere in solarized soil (39,40).

Greenberger et al. (14) demonstrated that solarized soils are often more suppressive to certain soilborne pathogens than nonsolarized soils. Pullman et al. (34) reported the effectiveness of solarization against *Verticillium* wilt in successive cultivations of safflower and cotton and Katan et al. (20) showed long-term effects of soil solarization against *Fusarium oxysporum* f. sp. *vasinfectum* in cotton for over 3 years. Several species of *Phytophthora* have been reported to be sensitive to high temperatures achieved through soil solarization (17,30). Solarization for 6 weeks completely eradicated *P. cinnamomi* in South Africa (3) and controlled crown rot of cherry caused by *P. cambivora* for more than 12 months after treatment in Australia (49). Solarization reduced population densities of *F. oxysporum* f. sp. *vasinfectum* and *Verticillium dahliae* by 94 to 100% at 5 cm, by 67 to 100% at 15 cm, and by 54 to 74% at 25 cm (22), eliminated *V. dahliae* to a depth of 120 cm in a pistachio grove without damaging the trees (1), and reduced the incidence of *Verticillium* wilt of potato in Idaho (11). Similarly, solar heating has shown promise for reducing *Agrobacterium tumefaciens* (35) and plant-parasitic nematodes (43). Solarization has the added advantages of being safe and nonchemical and may enhance the effectiveness of other pest management approaches, such as biological control (42) and soil fumigation (4).

Cover cropping followed by incorporation of plant residues into soil has been reported to suppress certain soilborne pathogens and root diseases (10). The efficacy of various organic amendments for controlling soilborne plant pathogens has been attributed to the formation of toxic volatile compounds or to an increase in antagonistic soil microflora (37). For example, brassicas, which contain glucosinolates that break down to toxic isothiocyanates (48), and Sudan grasses, which contain dhurrin that breaks down to hydrogen cyanide, have been reported to control phytonematodes (15,27) and pathogenic fungi (29,40). Not only can green manures provide an alternate disease control approach, they may increase nutrient availability, reduce ground water contamination, and stimulate beneficial microflora in the soil (2). Adding organic residues to the soil may increase the benefits of solarization (37).

In the Pacific Northwest, the nursery industry is a major agricultural sector with

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annual farmgate revenues in excess of \$400 million. Soilborne pathogens and pests cause substantial losses in many perennial, herbaceous, and woody nursery crops in the Pacific Northwest. In Oregon, hundreds of thousands of dollars of nursery crops are estimated to be lost due to *V. dahliae* and *Phytophthora* spp. on an annual basis. Crown gall, caused by pathogenic *Agrobacterium* spp., is also an economically important disease in Oregon nursery crops. Affected fruit trees and ornamental plants are not marketable and can cause severe economic losses to nurseries (35). Plant parasitic nematodes, such as *Pratylenchus penetrans*, have minor direct impact on plant growth in nursery production in the Pacific Northwest, but nematode-infested plants may not receive the phytosanitary certification required for interstate shipment. Solarization has been used successfully to control Verticillium wilt, crown gall, *Phytophthora* root rot, and plant-parasitic nematodes in subtropical and hot, arid regions, but its efficacy in controlling these pathogens in the temperate climate of the Pacific Northwest is unknown, with the exception of *Agrobacterium* spp. (35).

The objective of this study was to determine if solarization and cover cropping are feasible alternatives for simultaneously controlling a variety of important pathogens on nursery crops grown in the Pacific Northwest. These pathogens were *Phytophthora cinnamomi* Rands, *V. dahliae* Kleb., *A. rhizogenes* (Smith & Townsend 1907) Conn 1942, and *Pratylenchus penetrans* (Cobb) Filipjev and Schuurmans-Stekhoven. Aspects evaluated in this study included determining whether climatic conditions in Oregon are adequate for soil solarization; and comparing soil solarization, cover cropping, soil fumigation, and combinations of these treatments for reducing populations of these pathogens or the severity of infection caused by them.

MATERIALS AND METHODS

Inocula production. An environmentally competent spontaneous mutant of pathogenic *A. rhizogenes* strain B49C/83 originally isolated from an apple tumor and resistant to rifampicin was selected for infesting field plots. The bacteria were grown on mannitol glutamate medium (28) with 1 g liter⁻¹ of yeast extract substituted for biotin (MGY) and amended with 100 mg liter⁻¹ of rifampicin. Bacteria were washed off the surface of the agar plates and suspended in water to give a final reading of 125 in a Klett Summerson colorimeter (10⁹ CFU ml⁻¹).

The isolate of *Phytophthora cinnamomi* used in this study was originally obtained from western azalea (*Rhododendron occidentale*) in Oregon. *Phytophthora* spp. inoculum was prepared by growing the isolate in culture bags (L. F. Lambert Spawn Corp., Coatesville, PA) containing

500 cm³ of sieved vermiculite (>2 mm), 40 cm³ of ground oats, and 250 ml of V8 broth (V8 juice, 200 ml; CaCO₃, 2 g; and distilled water, 800 ml). The bags were autoclaved for 60 min on two consecutive days, allowed to cool, and inoculated with plugs taken from the margin of colonized corn meal agar (CMA) plates. After 3 weeks of incubation in the dark at 20°C, the colonized blocks of inoculum were broken up in a food processor and evenly mixed in a 1:10 ratio with sterilized field soil in a cement mixer. Inoculum density in the 1:10 soil-inoculum mixture was assayed with a leaf disk method described below.

The culture of *V. dahliae* used in this study was originally isolated from Norway maple (*Acer platanoides*) obtained from a commercial nursery in Oregon. *V. dahliae* inoculum was prepared by growing single-spore isolates in culture bags containing 1,100 cm³ of soaked rye grain. The bags were autoclaved for 60 min on two consecutive days, allowed to cool, inoculated with 10 ml of colonized Czapek-Dox broth, and incubated in the dark at 25°C. After inoculating, the bags were shaken by hand every 3 or 4 days to keep the cultures from becoming solid masses. After full colonization of the rye (4 to 6 weeks), the grain was spread out on an open bench top to dry, then ground into a powder with a Wiley mill (A. H. Thomas Co., Philadelphia, PA) utilizing a 20-mesh screen. The inoculum density (CFU g⁻¹) of this powder was determined by the Andersen sampler technique (6) described below.

The effects of treatment on populations of *Pratylenchus penetrans* were only studied in 1995 in two fields at the Oregon State University (OSU) Botany and Plant Pathology Field Laboratory in Corvallis. One field had silty-clay loam and the other field had a loam soil. In April 1994, peppermint plants infested with >1,000 *P. penetrans* per gram of root were planted at a density of 9 plants/m² in each 2-by-2-m plot. After 12 months and before planting the cover crops, an aqueous solution of 1% glyphosate was applied to kill the stand of peppermint and weeds covering the plots.

Plot establishment. Field experiments were conducted during the summers of 1995 and 1996 in separate but adjacent plots on a silty-clay loam soil at the OSU Field Laboratory in Corvallis. Preceding solarization, each field had been left in weedy fallow for 4 years. On 22 May 1995 and 4 June 1996, *V. dahliae*, *Phytophthora cinnamomi* inocula, and urea (46-0-0 at 34 kg ha⁻¹) were broadcast on the surface of the soil and the plots were rototated immediately to incorporate the inocula uniformly to a depth of 20 cm. Seed of the cover crops were broadcast on the soil surface and incorporated with light raking. Seeding rates were Trudan 8 sorghum-Sudan grass hybrid (*Sorghum bicolor* × *S. vulgare*), 111 kg ha⁻¹; Mica barley

(*Hordeum vulgare*), 133 kg ha⁻¹; and Dwarf Essex rape (*Brassica napus*), 33 kg ha⁻¹. Cover crops were irrigated and weeded according to recommended practices for nursery production prior to incorporation in July. The experimental design in 1995 was a randomized split plot with four replications. An extra replicate and a methyl bromide treatment were added to the experimental design in 1996. The whole plots consisted of solarized and nonsolarized soils. Subplots consisted of (i) incorporated green manures, (ii) application of metam sodium, (iii) clean fallow, (iv) methyl bromide (nonsolarized plots in 1996 only), and (v) control plots not inoculated with any of the pathogens. Each treatment subplot was 2 by 2 m in size.

The depth to which solarization was effective was determined by burying nylon bags of artificially infested soil at various depths in each plot. This soil was prepared by mixing the following uniformly in a cement mixer: *V. dahliae* inoculum, 1.31 × 10⁻³ g; *P. cinnamomi* inoculum, 1.11 × 10⁻¹ g; 60 ml of distilled water, and 1 kg of sterilized silty-clay loam soil. A total of 250 cm³ of the mixture was loosely placed into fine nylon mesh bags (Legg's Products Inc., Henderson, NV) along with a plastic label to identify sample name and depth. The bags were knotted at the end and attached to monofilament lines with labels to assist in their recovery. These inoculum bags were buried in the soil within 48 h of preparation in respective plots.

Treatments. In mid-July of 1995 and late July of 1996, the cover crops were cut at ground level, chopped into pieces 10 to 15 cm long, and fresh weights were recorded. Before incorporating the green manure, each 2-by-2-m plot was sprayed with 2 liters of a 1 × 10⁹ CFU ml⁻¹ aqueous suspension of *A. rhizogenes*. Crop residue was spread over the plot from which it was harvested and the plots were rototated to a depth of 20 cm. Fallowed and metam sodium-treated plots also were rototated. At this time, two sets of nylon bags containing fungal inocula were buried in each plot at depths of 5, 10, and 20 cm in 1995 and at depths of 5, 10, 20, and 30 cm in 1996. Plots were irrigated with an overhead sprinkler to bring the soil to field capacity. A 0.6-mil transparent polyethylene film (PolySource, San Diego, CA) was stretched tightly over the plots to be solarized and secured in place by burying the edges. The plots were solarized for 59 or 54 days from 21 July to 19 September and from 26 July to 18 September in 1995 and 1996, respectively. Nonsolarized plots were maintained weed free with applications of glyphosate and hand weeding during the solarization period. The metam sodium treatments were applied immediately after the July rototivation. Metam sodium was sprayed on the soil surface at 930 (nonsolarized) and 230 liters ha⁻¹ (solarized and nonsolarized) in 2 liters of

water per plot. The soil was rotovated immediately and then rolled to seal the surface. In 1996, subplots were tilled and prepared as before, and a methyl bromide with 2% chloropicrin treatment was applied at 800 kg ha⁻¹.

Sampling. Soil samples were collected on four dates: immediately after infesting the plots, after incorporating the green manures, after 4 weeks of solarization, and when the solarization plastic was removed. Those dates were 22 May, 21 July, 18 August, and 19 September, respectively, in 1995 and 4 June, 26 July, 23 August, and 18 September, respectively, in 1996. Population densities of all introduced pathogens and selected beneficial microorganisms were determined in samples for each date. Eight soil cores (2.5 by 30 cm) were collected from each plot, bulked, and thoroughly mixed for analysis. In addition, one inoculated soil bag in each plot from each depth was removed after 4 weeks and the second bag was collected when the plastic was removed.

Soil temperatures were recorded hourly in solarized and nonsolarized plots at depths of 5, 10, and 20 cm in 1995 and at 5, 10, 20, and 30 cm in 1996. A thermistor was placed at the given depths in the center of each plot and mean hourly temperatures were recorded with a CR21 micrologger (Campbell Scientific, Logan, Utah).

Assay procedures. A 100-g subsample of the bulked soil samples was processed for nematodes by the Baerman funnel method (46) for 5 days. All plant-parasitic nematode genera were counted in the samples collected at each date. A second set of subsamples was oven dried overnight at 121°C to determine the sample moisture content. Nematode population densities were standardized to a base line of 100 g of dry soil.

Agrobacterium spp. counts were made from soil samples taken in July and in September. Two soil samples of 10 g each were used, one sample to determine moisture content and the other for bacterial counts. Bacterial counts were made by suspending 10 g of soil in 90 ml of sterile water in 250-ml flasks, then shaking these flasks on a rotary shaker for 1 h. Serial dilutions were made from each suspension and three dilutions were spread plated in triplicate. Counts for *Agrobacterium* strain B49C/83 were made on selective medium 2E of Brisbane and Kerr (5) amended with 100 mg liter⁻¹ rifampicin.

Natural populations of beneficial bacteria also were monitored in July before solarization and in September after solarization. These soil samples were processed in the same manner as the *Agrobacterium* spp. samples. Spore-forming bacteria (*Bacillus* spp.) were detected by heating soil suspensions to 80°C for 10 min, then plating on nutrient agar amended with 0.2 g liter⁻¹ cycloheximide. Fluorescent pseudomonads were counted on King B me-

dium (28) amended with 0.2 g liter⁻¹ cycloheximide, and actinomycetes were enumerated by plating on MGY amended with 0.2 g liter⁻¹ cycloheximide.

The double-cup leaf disk method described by Linderman and Zeitoun (25) was used to recover and semiquantify *P. cinnamomi* from the bagged, artificially infested soil. A Styrofoam cup with its bottom replaced by a layer of cheesecloth was nested over 10 g of soil in a second intact cup. Twelve leaf disks (9 mm in diameter) of eucalyptus (*Eucalyptus gunnii*) were floated in a hymexazol solution (25 µg ml⁻¹) above the cheesecloth and soil for 3 days at room temperature under fluorescent lighting. The leaf disks were removed from the cups, blotted dry, and placed into PARP medium (pimaricin, vancomycin, rifampicin, PCNB) amended with 50 µg ml⁻¹ hymexazol (16). Plates were incubated in the dark for 72 h and examined for growth of *P. cinnamomi*. The estimate of inoculum quantity in a soil sample was expressed as percent colonized leaf disks.

The Andersen sampler technique (6) was used to estimate *V. dahliae* populations in field and bagged soil. Soil aggregates from each sample were broken up and thoroughly mixed. After air drying the soil at room temperature for 1 week, each sample was ground into a fine powder with a mortar and pestle. An Andersen air sampler was used to distribute the soil on the surface of NP-10 medium (38). Four replicate plates were processed for each sample. After 10 days of incubation in the dark at 20°C, the surface of the agar medium was gently washed under a stream of water to remove soil particles, and microsclerotial colonies of *V. dahliae* were counted with the aid of a dissecting microscope. The estimate of soil inoculum density was expressed as an average number of CFU of *V. dahliae* g⁻¹ of dry soil.

Soil bioassay. Snapdragons, hybrid Liberty Crimson (*Antirrhinum majus*, Goldsmith Seeds, Inc., Gilroy, CA), grown from seed in plug trays (Cyberplast Industries Ltd., Beaverton, MI), were used as indicator plants for the detection of *P. cinnamomi* in bagged soil. Ten-cell plastic plug trays were surface sterilized with 0.5% NaOCl and cotton plugs were placed in the bottom of the cells. Trays were filled with a soil sample (5 g of soil per 50-ml cell) and a single 4-week old snapdragon seedling plug was transplanted into each of the 10 cells and watered. Each 10-cell tray was placed on a wire mesh bench in the greenhouse, to eliminate the probability of cross contamination between samples, and arranged randomly. Control treatments consisted of snapdragons planted in autoclaved and oven-dried field soil. After 7 weeks, the plant heights were measured and plants were assessed for symptoms of infection (i.e., wilting, stunting, or death). Symptomatic and asymptomatic snapdragon roots

from each treatment were assayed for *P. cinnamomi*. Roots were disinfested by thoroughly washing the root system in tap water for 10 min, blotting dry, cutting the roots into 1-cm sections with a sterile scalpel, and plating on PARP amended with 50 µg ml⁻¹ hymexazol. Plates were incubated in the dark at 20°C for 1 week and checked for *P. cinnamomi*.

Eggplants, cv. Imperial Black Beauty (*Solanum melongena* L.), grown from seed were used as indicator plants for the detection of *V. dahliae* in 1996. Soil samples were removed from cold storage and mixed thoroughly. A 25-g subsample of each was placed on top of sterilized potting mix in a 160-ml "super cell" tube (Ray Leach Container, Stuewe and Sons, Corvallis, OR) into which a 4-week-old eggplant was transplanted. Because of space limitations, treatment comparisons were restricted to samples buried below 5 cm where plating assay indicated greater survival of microsclerotia. Control plants were planted in sterilized field soil. In the greenhouse, all eggplants were fertilized once a week with a water-soluble fertilizer (20-20-20 Peters; Scott-Sierra Co., Marysville, OH). After 8 weeks, the plants were harvested and the roots and shoots of each eggplant were dried and weighed to measure total plant biomass and to assess treatment differences. Symptomatic and asymptomatic roots from each treatment were assayed for *V. dahliae*. Roots were surface disinfested with 0.05% NaOCl for 15 sec, rinsed with sterile water, cut into 1-cm pieces, and plated on NP-10 media. Plates were incubated in the dark at 24°C for 2 weeks and checked for characteristic *V. dahliae* growth.

Eight months following solarization, 25 euonymus plants (*Euonymus japonica*) 50 to 100 'Mazzard' cherry trees (*Prunus avium*), and 25 maple trees (*Acer rubrum* in 1996 and *A. plantoides* in 1997) were planted in all plots to determine the level of field plant infection due to *P. cinnamomi*, *A. rhizogenes*, and *V. dahliae*, respectively. All plants were root pruned prior to planting to promote infection by *A. rhizogenes*. After 12 months, the cherry trees were dug and the number of galls on the roots were counted. At this time, the height of the maple trees was measured and the trees were rated for symptoms of Verticillium wilt. Verticillium ratings were assigned to five categories, where 1 = no symptoms, 2 = few to 9% of leaves symptomatic, 3 = 10 to 49% of leaves symptomatic, 4 = >50% of leaves symptomatic of Verticillium wilt, and 5 = dead tree. Because of poor initial survival of euonymus plants, the field assay for Phytophthora root rot was discontinued.

Data analysis. Significance of treatment differences was determined with SAS (SAS Institute, Inc., Cary, NC) by analysis of variance (ANOVA) using the general linear model procedure. Means were sepa-

rated by least significant difference using Waller-Duncan tests.

RESULTS

Soil temperatures. The maximum soil temperatures recorded during both years in the upper 20 cm of soil were 10 to 16°C higher in solarized plots than in the non-solarized plots (Table 1). Maximum soil temperatures reached in solarized plots were 53, 48, 39, and 34°C at 5, 10, 20, and 30 cm, respectively. The seasonal pattern of daily maximum soil temperatures was similar in both years, so only the 1996 data are presented (Fig. 1). As an estimation of the thermal dose achieved in each season, the cumulative hours of temperatures greater than 35, 40, and 45°C were calculated (Table 1).

Verticillium spp. evaluation. All treatments, except nonsolarized Sudan grass in 1995, significantly reduced *V. dahliae* population densities in bulk field soil compared to the nonsolarized control after 2 months of solarization (Table 2). Green manure crops were not as effective as solarization in reducing *Verticillium* spp. densities, nor did they enhance the efficacy of solarization. In 1995, solarization reduced *V. dahliae* populations as effectively as metam sodium at 930 liters ha⁻¹, but metam sodium and methyl bromide were more effective than solarization in 1996. Survival of *V. dahliae* propagules from buried bags of soil decreased in all treatments at all depths compared to the control, but this effect diminished with increasing depth (Table 3). In the upper 5 and 10 cm, solarization treatments were as effective as soil fumigation and significantly better than green manure treatments. At 20 and 30 cm, the survival of *V. dahliae* indicated that solarization was no more effective than green manure treatments. Fumigation with methyl bromide or metam sodium at 930 liters ha⁻¹ gave significantly greater control of *V. dahliae* at 20 and 30 cm compared to all other treatments. At all depths, the 230 liters ha⁻¹ rate of metam sodium, with or without solarization, was never more effective than other solarization treatments.

Red maple trees planted in the plots treated in 1995 remained asymptomatic of

Verticillium wilt through 1998. Norway maple trees planted in plots treated in 1996 developed symptoms of Verticillium wilt in 1998 and were visually rated in July 1998. The ranking of treatments by disease ratings (Table 4) and tree height corresponded with the *Verticillium* spp. population densities determined by plating bulk field soil. Trees planted in soil fumigated with methyl bromide were symptomless and taller than trees in the other treatments. Trees grown in solarized plots generally had a lower disease rating and were taller than the trees in the paired, nonsolarized treatment, but those differences were not significant ($P > 0.05$).

Weights of eggplants planted in soil that had been buried at 10 and 20 cm were greater ($P < 0.01$) for solarized than non-solarized soil (Table 5). At 30 cm, the effects of solarization were only evident in soil from the barley plots. Biomass of eggplants was greater in fumigated soils than in solarized soils. *V. dahliae* was isolated only from the roots of symptomatic eggplants grown in inoculated soil and not from roots of plants grown in fumigated soil.

Phytophthora spp. evaluation. We were unable to quantify *P. cinnamomi* from bulk soil because a hymexazol-resistant *Pythium* sp. present in this soil grew rapidly over the PARP medium in bait leaf assays. However, *Phytophthora cinnamomi* was semiquantified in baited leaf assays of artificially infested soil that was buried in bags. In assays of soil before burying the bags, 100% of the leaf disks were infected. In both years, solarization reduced *P. cinnamomi* to below detectable levels in the upper 10 cm and was as effective as soil fumigation with metam sodium and methyl bromide (Table 6). At 20 and 30 cm, a lower percentage of disks ($P < 0.01$) were infected in assays of solarized and fumigated soil than in soil collected from non-solarized plots. Solarization was as effective as fumigation at 20 cm in 1995 and 1996. Green manures reduced ($P < 0.01$) recovery of *P. cinnamomi* at 5 and 10 cm compared to the control, but they did not enhance the efficacy of solarization.

Results of the snapdragon bioassay were not significantly different between years; hence, only the 1996 data are presented (Table 6). The mean height of assay plants

Fig. 1. Maximum daily soil temperature at four depths in solarized and nonsolarized plots at Corvallis, OR from 26 July to 18 September 1996.

Table 1. Soil temperatures in solarized and nonsolarized plots in 1995 and 1996^a

Solarization period	Depth (cm)	Soil temperature (°C)				Cumulative hours in solarized plots		
		Solarized plots		Nonsolarized plots				
		Mean	Maximum	Mean	Maximum	>35°C	>40°C	>45°C
21 July–19 Sept. 1995	5	31.7	49.3	23.2	34.5	399	195	53
	10	33.1	45.9	23.4	31.2	445	160	9
	20	31.0	37.4	22.8	27.4	75	0	0
26 July–18 Sept. 1996	5	29.3	52.6	22.9	37.0	309	169	66
	10	31.7	47.6	23.6	32.7	390	152	17
	20	29.9	39.1	22.4	28.0	101	0	0
	30	29.2	33.6	22.2	25.4	0	0	0

^a Thermocouples were buried at each depth in one solarized and one nonsolarized plot. Temperatures were recorded hourly by a datalogger. Plots were located in adjacent fields of silty clay soil on the Oregon State University Plant Pathology Field Station at Corvallis.

grown in soil from the various treatments were in close agreement with the percent infection in the leaf-baiting assay. Snapdragons grown in infested soil that had been buried at 10 and 20 cm in solarized plots were taller ($P < 0.01$) than plants grown in soil from the paired, nonsolarized plots. There were no differences in heights ($P < 0.01$) between plants grown in solarized, fallow soil and in soil from fumigated plots. *P. cinnamomi* was isolated only from

symptomatic seedling roots; no symptoms were observed in plants grown in non-inoculated control soil or sterilized field soil.

Agrobacterium spp. evaluation. Population densities of rifampicin-resistant *Agrobacterium* spp. in bulk field soil declined significantly in 1995, but not in 1996, in all solarized and fumigated plots (Table 2). ANOVA of paired, homologous solarized and nonsolarized plots showed that *Agrobacterium* spp. counts were sig-

nificantly lower ($P < 0.01$) in solarized compared to nonsolarized plots in all cover crop and fallow treatments. The incidence of galls on cherry trees planted in the 1995 plots was negligible, but in the 1996 plots, the percentage of cherry trees with galled roots was significantly lower in solarized plots compared to nonsolarized plots (Table 4). Methyl bromide did not reduce the incidence of trees with galls below that of the solarization control.

Table 2. Effects of soil solarization, green manures, and fumigation on the population densities of introduced soilborne plant pathogens in the upper 30-cm soil profile^a

Treatment	<i>V. dahliae</i> ^y		<i>Agrobacterium</i> spp. ^w		<i>P. penetrans</i> ^x	
	1995	1996	1995	1996	1995	1995 loam
Control, noninfested	0.0 d	2.5 e	1.05 a	2.83 bcd	NT	NT ^y
Control, solarized	4.7 cd	51.9 c	2.19 b	2.41 bc	4	6 a
Control, nonsolarized	39.8 a	140.0 a	4.25 de	3.77 cde	10	29 b
Barley, solarized	3.1 cd	25.6 d	3.04 cde	3.09 bcde	14	NT
Barley, nonsolarized	6.3 c	54.4 c	4.30 ef	3.79 cde	19	NT
Rape, solarized	5.1 cd	47.5 c	2.68 bc	2.57 bcd	3	NT
Rape, nonsolarized	21.9 b	90.0 b	4.56 fg	3.95 de	29	NT
Sudan, solarized	3.9 cd	45.0 c	2.37 bc	2.51 bcd	3	NT
Sudan, nonsolarized	38.3 a	86.9 b	5.13 g	4.40 e	20	NT
Metam 230, solarized	4.3 cd	50.0 c	2.44 b	1.96 ab	1	NT
Metam 230, nonsolarized	16.8 b	84.4 b	3.70 de	3.24 bcde	2	NT
Metam 930, nonsolarized	2.7 cd	8.8 e	3.00 ef	0.91 a	3	NT
Methyl bromide, nonsolarized	NT	0.6 e	NT	1.86 ab	NT	NT
Initial inoculum density	91 ^z	203	5.52	5.53	37	42

^a Plots were located on adjacent fields of silty clay soil or on a field of loam soil on the Oregon State University Plant Pathology Field Station at Corvallis. *Verticillium dahliae* and *Agrobacterium* spp. were broadcast on the soil and incorporated to approximately 20 cm. *Pratylenchus penetrans* was introduced on infested peppermint plants planted in 1994. Solarized plots were covered with a 0.6-mil clear polyethylene film for 2 months from mid-July to mid-September. Cover crops were planted in May each year and incorporated as green manures in mid-July. Metam sodium was applied on the soil surface at 230 or 930 liters ha⁻¹ and mechanically incorporated. Methyl bromide was applied at 820 kg ha⁻¹ under a plastic film. Means within columns followed by different letters were significantly different ($P < 0.01$) according to the Waller-Duncan procedure. No letters indicate no significant differences.

^y Post-solarization population densities (CFU g⁻¹ dry soil), 22 May 1995 and 4 June 1996.

^w Post-solarization population densities (log₁₀ CFU g⁻¹ dry soil), 19 September 1995 and 18 September 1996.

^x The 1995 study compared cover crop, solarization, and fumigation treatments on a silty clay soil; 1995 loam study compared only solarized and nonsolarized treatments on a loam soil. Post-solarization population densities (nematodes 100 g⁻¹ dry soil in upper 30-cm soil profile), 19 September 1995.

^y No treatment was made.

^z Initial mean population densities in June.

Table 3. Population densities of *Verticillium dahliae* in artificially infested soil after two months burial at three depths in solarized, fumigated, or cover-cropped field plots at Corvallis, OR^w

Treatment ^y	<i>V. dahliae</i> counts (CFU g ⁻¹ dry soil) ^x						
	1995			1996			
	5 cm	10 cm	20 cm	5 cm	10 cm	20 cm	30 cm
Control, solar	4.5 d	22.5 de	57.0 b	1.2 c	12.8 de	42.0 de	75.2 bcd
Control, nonsolar	101.5 a	115.3 a	170.8 a	162.6 a	189.2 a	203.2 a	204.4 a
Barley, solar	2.8 d	5.0 fg	22.5 ef	0 c	6.4 efg	25.2 e	47.6 e
Barley, nonsolar	50.3 c	35.8 c	27.0 e	12.6 b	23.0 cd	38.8 de	48.2 e
Rape, solar	0 d	2.5 g	30.8 de	0 c	1.8 efg	43.8 de	57.4 de
Rape, nonsolar	75.5 b	49.5 b	40.3 cd	19.6 b	41.4 b	65.6 bc	91.4 b
Sudan, solar	0.5 d	4.8 fg	12.5 fg	1.2 c	11.2 ef	46.8 cd	62.6 cde
Sudan, nonsolar	58.0 c	31.3 cd	42.0 c	19.4 b	33.6 bc	78.8 b	87.0 bc
Metam 230, solar	2.8 d	14.8 ef	46.8 bc	0.6 c	3.0 efg	30.0 de	71.4 bcde
Metam 230, nonsolar	0.5 d	9.0 fg	47.3 bc	1.8 c	10.4 efg	39.4 de	69.0 bcde
Metam 930, nonsolar	1.8 d	2.3 g	7.3 fg	0 c	1.2 fg	3.8 f	5.0 f
Methyl bromide, nonsolar	NT ^z	NT	NT	0 c	0 g	0.6 f	1.2 f

^w *V. dahliae* inoculum was grown on rye grain, ground, and mixed into pasteurized silty clay loam soil collected from the field plots to yield 302 and 234 CFU g⁻¹ soil in 1995 and 1996, respectively. Infested soil was placed in nylon mess bags and buried in plots in at the start of the solarization period.

^x Soil was dispersed on Sorensen's NP-10 medium with a Andersen sampler. *Verticillium* spp. colonies were counted after 10 days. Mean values within columns followed by different letters were significantly different ($P < 0.01$) according to the Waller-Duncan procedure.

^y Solarized plots were covered with a 0.6-mil clear polyethylene film for 2 months from mid-July to mid-September. Cover crops were planted in May each year and incorporated as green manures in late July. Metam sodium was applied on the soil surface at 230 or 930 liters ha⁻¹ and mechanically incorporated. Methyl bromide was applied at 820 kg ha⁻¹ under the plastic film.

^z No treatment was made.

Pratylenchus spp. evaluation. Solarization reduced the population densities of *P. penetrans* compared to the paired non-solarized treatments in 1995 (Table 2). Because of the great variability in nematode population densities at the start of the study, these differences were statistically significant only in the loam soil. Fumigation with metam sodium was no more effective in reducing *P. penetrans* population densities in the silty-clay loam soil than solarization alone. None of the treatments depressed nematode densities below the detection threshold.

Beneficial soil microflora. Spore-forming bacteria and fluorescent *Pseudomonas* spp. populations were stable in soil plots where cover crops, soil solarization, and low levels of metam sodium were

used. However, population densities of these two groups of organisms were significantly lower in plots where methyl bromide was used than in nontreated controls. Population densities were similar for actinomycetes regardless of the treatments.

DISCUSSION

Soil solarization is known to control soilborne pathogens and pests in subtropical and southern desert regions (21), but there are limited data on its efficacy in the temperate latitudes (11,24,35). Western Oregon, because of its Mediterranean climate (with maximum daily temperatures 25 to 40°C and little cloud cover during the summer), should be amenable to solarization. At depths between 5 to 20 cm, the maximum soil temperatures achieved in

this study were within the range of temperatures documented at comparable depths in California (34), Israel (21), and Florida (7). At a 30-cm depth, the maximum temperature recorded was 34°C in 1996, which is 4 to 7°C lower than temperatures reported from California (34). At the times of solarization, meteorological conditions were considered normal for western Oregon; therefore, it is anticipated that the reported effects should be repeatable most years.

The efficacy of soil solarization is dependent on the thermal dose (33), a product of the temperature and exposure time, the thermal sensitivity of the organisms, and the chemical, physical, and biological characteristics of the soil, including the moisture content (42). In our study, thermal doses in the upper 10 cm, approximately 150 h above 40°C and 10 h above 45°C, were observed each year. These temperatures are in the range of those found to be lethal to many pathogens (2). At 20 and 30 cm, the thermal dose was much lower, but population densities of the pathogens were still reduced, although to a lesser degree. This phenomenon may be due to the cumulative effect of sublethal temperatures on the pathogens (11,45) or to a combination of biological and thermal control, such as increased microbial antagonism or a breakdown in fungistasis (19). There were no significant differences in population densities of the pathogens isolated from soil after 1 or 2 months of solarization; therefore, overall exposure time may be reduced below that tested in this study. However, most nursery crops in the Pacific Northwest are planted in the spring or fall, so there would be no advantage in removing the tarp before the soil is tilled in the fall.

Solarization gave significant reduction in soil population densities of *Phy-*

Table 4. Disease assessment of maple and cherry trees planted in field plots at Corvallis, OR in May 1997, 8 months after solarization was terminated^w

Treatment ^x	Disease rating ^y	Trees with galls (%) ^z
Control, noninoculated	0.7 b	3.3 cde
Control, solar	1.5 cd	0.7 e
Control, nonsolar	2.0 de	9.1 abcd
Barley, solar	1.6 cde	0.4 e
Barley, nonsolar	1.9 de	9.5 abc
Rape, solar	1.9 de	1.3 e
Rape, nonsolar	2.1 e	14.2 a
Sudan, solar	1.5 cd	2.3 de
Sudan, nonsolar	2.0 de	10.6 ab
Metam 230, solar	1.2 bc	0.0 e
Metam 230, nonsolar	1.9 de	3.5 bcde
Metam 930, nonsolar	1.3 c	1.4 e
Methyl bromide, nonsolar	0.2 a	4.4 bcde

^w Evaluated in July 1998. Mean values within columns followed by different letters were significantly different ($P < 0.01$) according to the Waller-Duncan procedure.

^x Solarized plots were covered with a 0.6-mil clear polyethylene film for 2 months from mid-July to mid-September. Cover crops were planted in May each year and incorporated as green manures in late July. Metam sodium was applied on the soil surface at 230 or 930 liters ha⁻¹ and mechanically incorporated. Methyl bromide was applied at 820 kg ha⁻¹ under a plastic film.

^y *Verticillium dahliae* field maple assay. Rating scale: 1 = no symptoms, 2 = few to 9% of leaves symptomatic, 3 = 10 to 49% of leaves symptomatic, 4 = >50% of leaves symptomatic of Verticillium wilt, and 5 = dead tree.

^z *Agrobacterium* spp. field cherry assay. Trees were dug and inspected for gall on roots and crown.

Table 5. Greenhouse bioassays of artificially infested soil after two months burial in solarized, fumigated, and cover-cropped field plots at three soil sample depths in Corvallis, OR during 1996^w

Treatment ^z	Mean snapdragon height (cm) ^x			Mean eggplant biomass (g) ^y		
	10 cm	20 cm	30 cm	10 cm	20 cm	30 cm
Control, sterilized field soil	19.92 a	19.92 a	19.92 a	6.04 a	6.04 a	6.04 a
Control, solar	20.0 a	18.83 ab	16.17 ab	4.19 d	3.97 c	3.31 de
Control, nonsolar	9.67 de	9.50 cd	7.67 de	3.42 e	3.17 de	2.84 def
Barley, solar	17.88 ab	12.25 c	11.0 cd	4.64 cd	3.95 c	4.25 c
Barley, nonsolar	12.88 cd	8.5 d	5.88 e	3.07 ef	3.09 e	2.58 ef
Rape, solar	19.38 a	15.88 b	11.25 cd	4.5 cd	3.38 cde	3.02 def
Rape, nonsolar	9.50 e	9.75 cd	6.88 de	2.33 f	2.33 f	2.52 f
Sudan, solar	19.88 a	17.13 ab	13.88 bc	5.03 bc	3.84 cd	3.37 d
Sudan, nonsolar	15.25 bc	10.75 cd	9.88 cde	2.65 f	3.21 de	2.82 def
Metam 230, solar	19.5 a	17.5 ab	13.13 bc	5.04 bc	4.94 b	5.22 b
Metam 930, nonsolar	20.0 a	19.63 a	19.13 a	5.63 ab	5.02 b	6.44 a

^w *Phytophthora cinnamomi* and *Verticillium dahliae* inoculum was mixed into pasteurized field soil and buried in nylon mesh at the start of the solarization period. Mean values within columns followed by different letters were significantly different ($P < 0.01$) according to the Waller-Duncan procedure.

^x *P. cinnamomi* bioassay: 10 snapdragon plants were planted in plug sheet cells that contained 5 g of soil from each buried bag mixed in pasteurized field soil. After 7 weeks, plant height was measured.

^y *V. dahliae* bioassay: eggplants were planted in super cells that contained 5 g of soil from each buried bag mixed in pasteurized field soil. After 7 weeks, plants were harvested, air dried, and weighed.

^z Solarized plots were covered with a 0.6-mil clear polyethylene film for 2 months from mid-July to mid-September. Cover crops were planted in May each year and incorporated as green manures in late July. Metam sodium was applied on the soil surface at 230 or 930 liters ha⁻¹ and mechanically incorporated. Methyl bromide was applied at 820 kg ha⁻¹ under the plastic film.

trophthora cinnamomi and *V. dahliae* and subsequent infection by these pathogens of assay plants grown in solarized soil. It has been documented that chlamydospores of *P. cinnamomi* were completely inactivated by exposure to 38 to 41°C for 30 min (3), and that 20 min at 45°C completely killed propagules of *P. cinnamomi* in moist soil and infected walnut twigs (17). In our study, soil temperatures in the top 20 cm of solarized plots reached above 35°C for at least 75 h in each year. We believe that the thermal dose was sufficient to account for elimination of *P. cinnamomi* in the upper soil profile. At a depth of 30 cm, the lower thermal dose had less effect on the viability of *P. cinnamomi*, as has been previously reported for *P. cambivora* (49). *V. dahliae* is more tolerant of elevated temperatures, requiring a constant temperature of 45°C for 1 to 2 h to kill 90% of the microsclerotia under controlled environmental conditions (23). The thermal death curves previously determined (23,34) would predict the high mortality of *V. dahliae* inoculum observed in the upper 10 cm of the soil profile in our study, but not at lower depths. This prediction was supported by direct assay and bioassay of soils collected from each depth. The initial population densities of *V. dahliae* introduced into the 1996 plots were 50 to 100 times greater than those observed to cause economic loss in susceptible maples varieties in commercial nurseries in Oregon (R. Regan, *personal communication*). Solarization reduced *V. dahliae* densities to 5 and 25% of the initial density in 1995 and 1996, respectively. However, the inoculum remaining after solarization resulted in wilt severity that was intermediate to the severity observed in nonsolarized and fumigated

plots. Under the lower inoculum densities more typically found in nursery soils, solarization should provide better disease control.

Soil solarization has decreased population densities of both natural and introduced *Agrobacterium* spp. populations (35). Tests conducted in Italy in 1992 (35) with natural populations showed a decreased population density after soil solarization. Disease incidence was not reduced, however, and, in some cases, there was a slight increase in incidence of crown gall (35). In field experiments in Oregon, where pathogenic strains of *Agrobacterium* were seeded to soil in 1993 and 1994, *Agrobacterium* spp. populations were reduced well below those in the control plots, as was the incidence of crown gall on cherry rootstocks subsequently planted to those plots (35). The beneficial effect differed according to soil type. Populations of *Agrobacterium* spp. in sandy soil were no longer detectable after 6 weeks of solarization. In silty-clay soils, *Agrobacterium* spp. populations were still detectable after 8 weeks of soil solarization, but the population levels were much lower than those detected when solarization was initiated, indicating that the population was less vulnerable in heavier soils (39). Results from our 1995 and 1996 solarization experiments in silty-clay soil were similar to those reported previously by Raio et al. (35). There was a reduction in population densities of an introduced *Agrobacterium* strain and a corresponding reduction in the incidence of crown gall in cherry rootstock seedlings. This reduction in the population of *Agrobacterium* spp. was seen consistently in fallow soil as well as those plots with cover crops. Further studies in solar-

ized plots in Italy in 1997 revealed that 12 of 122 rifampicin-resistant isolates from solarized soil were no longer pathogenic and lacked a Ti plasmid. The 12 strains were identical in biochemical characteristics and total DNA fingerprints to the *A. rhizogenes* strain used to infest soil before solarization. All rifampicin-resistant isolates from nonsolarized soil were pathogenic (36). Therefore, it appears that soil solarization is a beneficial method for reducing the risk of crown gall disease due to lowered populations of agrobacteria and loss of the Ti plasmid.

Cover crops alone or in combination with soil solarization provided no added benefit in terms of reducing populations of *Agrobacterium* spp. Finally, it is noted that the population density of introduced *Agrobacterium* spp. pathogens was much higher than those occurring naturally in soil, and solarization, therefore, is likely to be effective in commercial nurseries.

One of the goals of this research was to find substitutes for soil fumigation. Therefore, the relative advantages and disadvantages of various methods must be considered. In our study, fumigation treatments were as effective as the solarization control treatment in reducing *Agrobacterium* spp. populations in 1996, but metam treatments were less effective than solarization in 1995. This effect also was true relative to the incidence of galled trees in the various plots; that is, all fumigation treatments were not significantly different from the solarized control. Other reports of the effect of soil fumigation on crown gall have been mixed. Deep et al. (12) found that Mazzard cherry seedlings grown in soil fumigated with chloropicrin or a combination of chloropicrin and methyl bro-

Table 6. Recovery of *Phytophthora cinnamomi* from artificially infested bag samples after 2 months' burial at three depths in solarized, fumigated, and cover-cropped field plots at Corvallis, OR^w

Treatment ^y	Mean <i>Phytophthora cinnamomi</i> baiting efficacy (%) ^x						
	1995			1996			
	5 cm	10 cm	20 cm	5 cm	10 cm	20 cm	30 cm
Control, solar	0 c	0 c	16.7 cd	0 d	0 d	11.7 cde	31.7 c
Control, nonsolar	87.5 a	93.8 a	100 a	88.3 a	100 a	100 a	100 a
Barley, solar	0 c	0 c	4.2 d	0 d	0 d	20 cd	48.3 bc
Barley, nonsolar	20.8 c	58.3 b	83.3 ab	30.0 c	73.3 b	83.3 b	95 a
Rape, solar	0 c	0 c	0 c	0 d	0 d	11.7 cde	36.7 bc
Rape, nonsolar	18.8 c	58.3 b	75.0 b	6.7 d	43.3 c	81.7 b	96.7 a
Sudan, solar	0 c	0 c	0 c	0 d	0 d	21.7 c	53.3 b
Sudan, nonsolar	58.3 b	75 b	87.5 ab	43.3 c	70 b	86.7 ab	93.3 a
Metam 230, solar	0 c	0 c	29.2 c	0 d	0 d	0 d	3.3 d
Metam 230, nonsolar	0 c	0 c	10.4 cd	0 d	0 d	6.7 de	11.7 d
Metam 930, nonsolar	0 c	0 c	0 c	0 d	0 d	0 d	0 d
Methyl bromide, nonsolar	NT ^z	NT	NT	0 d	0 d	0 d	0 d

^w *P. cinnamomi* inoculum was grown on oat-V-8 medium, finely divided, and mixed into pasteurized silty clay loam soil collected from the field plots. This infested soil was placed in nylon mesh bags and buried in plots at the start of the solarization period.

^x Eucalyptus leaf disks were floated in a hymexazol solution (25 µg ml⁻¹) above assay soil for 3 days at room temperature under fluorescent lighting and then disks were placed into PARP medium amended with 50 µg ml⁻¹ hymexazol. After 72 h of incubation, leaf disk were examined for growth of *P. cinnamomi* and the percent leaf disks colonized was calculated. Mean values within columns followed by different letters were significantly different ($P < 0.01$) according to the Waller-Duncan procedure.

^y Solarized plots were covered with a 0.6-mil clear polyethylene film for 2 months from mid-July to mid-September. Cover crops were planted in May each year and incorporated as green manures in late July. Metam sodium was applied on the soil surface at 230 or 930 liters ha⁻¹ and mechanically incorporated. Methyl bromide was applied at 820 kg ha⁻¹ under the plastic film.

^z No treatment was made.

mide had a higher incidence of crown gall than those grown in nonfumigated soil. Field experiments by Pu and Goodman (32) resulted in a 84% reduction in the incidence of crown gall on Chancellor grape in soil previously fumigated with Vorlex (active ingredient: 1-3 dichloropropene and isothiocyanate) at 38 liters ha⁻¹.

Comparisons between the effects of soil solarization and fumigation on beneficial organisms also must be considered. Fumigation by metam sodium showed population decreases ranging from 50 to 90% of total and culturable bacteria, depending upon the soil type (47). In the current study, population densities of spore-forming *Bacillus* spp. and fluorescent pseudomonads were reduced by methyl bromide, but were unchanged by solarization.

Our research demonstrated that solarization can reduce, but not eliminate, population densities of *Pratylenchus penetrans* in the upper 30-cm soil profile. This effect agrees with other reports showing that population densities of *Pratylenchus* spp. were reduced 50 to 100% to soil depths of 10 to 15 cm by solarization, but were not significantly reduced at depths below 15 cm (24,31). Reinfestation by nematodes migrating from depths below the zone where lethal temperatures were attained (24) may explain why the effects of solarization do not persist throughout the cropping season (7). Given these findings, solarization will not provide adequate control of nematodes in Pacific Northwest nurseries for crops which may have a zero tolerance for nematode infestations in plant materials shipped between states or internationally.

Soil amendments, including crop residues, can reduce the severity of disease caused by plant pathogens (26). Subbarao and Hubbard (44) reported that broccoli residue incorporated in soil reduced the population densities of *V. dahliae* microsclerotia and wilt of cauliflower, and that this effect was greatest at 35°C. Ramieriz and Munneke (37) observed that solarization enhanced the activity of amended cruciferous residues in controlling cabbage yellows caused by *Fusarium oxysporum* f. sp. *conglutinans*. It was suggested that fungitoxic gases from the decomposing plant residues trapped under the tarp were responsible for disease reduction. In our research, green manure crops alone were effective in reducing populations of *V. dahliae* and *Phytophthora cinnamomi*, but we did not observe a synergistic interaction between solarization and green manures. Davis et al. (10) reported that 2 to 3 years of cropping with corn or Sudan grass, and subsequent incorporation of the crop residue into the soil, reduced the severity of Verticillium wilt of potato. They hypothesized that root infection by *V. dahliae* was suppressed by nonpathogenic *Fusarium* spp. which increased in the soil during this period. In our experiments, reduction in

population densities of *V. dahliae* occurred both during 8 to 10 weeks of plant growth and after incorporation of residues. Although population densities of *V. dahliae* were reduced following green manure incorporation alone, disease was not decreased in assay plants grown in soil from these treatments.

Soil solarization is well suited for integrated pest management and has been shown to be an economical alternative to fumigation in the subtropics (8). This study demonstrated that conditions in the temperate climate of Oregon were adequate for solarization. Solarization resulted in a significant reduction in population densities of several important pathogens and the diseases which they cause, but in general it was not as effective as fumigation with methyl bromide or high rates of metam sodium for all pathogens at the high population densities used in this study. In temperate regions, solarization in the summer precludes income from the land for one cropping year. Most growers are reluctant to forego the income, at least while fumigants and pesticides are effective and available. However, solarization may be economical in nursery crop production. When plants are dug in the spring, the field can be solarized during the summer, and then replanted in the fall or the following spring. The added benefit of weed control (42) and minimal disturbance to beneficial microorganisms in the soil may make solarization an attractive alternative or supplement to chemical or biological control of pests and pathogens in nursery and other high-value crops.

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