Reductions in Inoculum Density of *Rhizoctonia solani* and Control of Belly Rot on Pickling Cucumber with Solarization

Anthony P. Keinath, Assistant Professor, Department of Plant Pathology and Physiology, Clemson University, Coastal Research and Education Center, Charleston, SC 29414-5341

ABSTRACT

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The effectiveness of soil solarization to reduce the level of *Rhizoctonia solani* in soil and control belly rot on cucumber fruit was evaluated in naturally infested soil. Solarization under clear polyethylene mulch for 5 to 6 weeks during July and August 1992 to 1994 was compared with application of chlorothalonil and no treatment in a randomized complete block design. During solarization in 1993 and 1994, the percentage of organic matter colonized by *R. solani* declined at 0 to 10 cm depth in solarized soil but did not change significantly in nonsolarized soil. After solarization, colonies of *R. solani* grew from 0.9, 7, and 2.8% of the organic matter fragments recovered from solarized soil in 1992, 1993, and 1994, respectively, compared with 23, 44, and 26% of the organic matter from nonsolarized soil. Population densities of fluorescent *Pseudomonas* spp. at 0 to 20 cm declined during solarization each year. In 1992 and 1994, thermotolerant fungi, which grew at 40°C, were more abundant in solarized than nonsolarized soil. *Penicillium* spp. accounted for a significantly greater percentage of thermotolerant fungi in heated than in nonheated soil each year. Solarization reduced belly rot severity on pickling cucumber in 1992 and 1994 compared with no treatment (4.8% versus 10.1% and 4.4% versus 12.9%, respectively), whereas chlorothalonil reduced severity in 1993 (4.0%) and 1994 (4.1%). Incidence of belly rot was reduced by solarization and chlorothalonil applications in 1993 and 1994 but not in 1992. Neither treatment significantly increased total weight of healthy fruit compared with the control. In 1994, healthy fruit in solarized plots had a higher market value than fruit in plots of the other two treatments, but after cost of the treatments was subtracted, returns did not differ. Soil solarization is an effective nonchemical method for reducing preplant levels of *R. solani*.

Additional keywords: cottony leak, *Cucumis sativus*

Soil solarization, applied alone or in combination with other disease management strategies, has been shown to reduce the inoculum density of many soilborne fungal pathogens, including *Verticillium dahliae* Kleb. (14,19,20,28), *Fusarium oxysporum* Schlechtend.:Fr. f. sp. *lycopersici* (Sacc.) W.C. Snyder & H.N. Hans. (3,14), *Pythium* spp. (10,20), *Sclerotium rolfsii* Sacc. (10,21), *Thielaviopsis basicola* (Berk. & Broome) Ferraris (20), and *Phytophthora nicotianae* Breda de Haan var. *parasitica* (Dastur) G.M. Waterhouse (3), and to suppress the diseases caused by these pathogens (14,20,21,28). Few studies have targeted *Rhizoctonia solani* Kühn, one of the most widespread and destructive soilborne pathogens. In vitro tests have demonstrated that mycelium of *R. solani* AG-4 is sensitive to heat. For example, *R. solani* was killed on 90% of agar disks exposed for 3.5 h to 45°C or 14 days at 39.1°C (19). Under clear polyethylene mulch, soil temperatures can be elevated to levels lethal to *R. solani*. *R. solani* was not detected at 0 to 15 cm depth in soil solarized for 28 days in which a maximum temperature of 48°C was recorded, while nonsolarized soil contained 4 CFU per 100 g (20). The incidence of Rhizoctonia stem canker and scurf of potato were reduced by 68 and 58% by soil solarization, respectively, and the percentage of diseased snap bean seedlings subsequently planted in the solarized soil was reduced by 60 to 100% (7). In another study, infection of iris bulbs by *R. solani* was reduced and yield was increased in solarized soil (4). These studies suggest that solarization could be used to reduce the inoculum density of *R. solani*, which is primarily confined to the upper soil layers, ≤20 cm depth (24).

In previous field trials in the humid southeastern United States, absolute maximum temperatures achieved in solarized soil were 49.5°C at 5 cm in northern Florida (3) and 49.3°C at 10 cm in North Carolina (21). These temperatures were less than those recorded in drier climates, such as 55°C at 5 cm in Israel (7), 60°C at 5 cm in California (20), or 57°C at 10 cm in Greece (28).

Several groups of saprophytic microorganisms respond dramatically to solar heating of soil: population densities of fluorescent pseudomonads decrease and those of thermotolerant fungi able to grow at 46°C usually increase (9,21,25,28), although significant decreases in thermotolerant fungi that grow at 40°C have been observed (9). Monitoring soil microflora that respond to heat could be used as a biological indicator of changes brought about by solarization, in addition to changes in pathogen populations and disease levels.

Belly rot, caused by *R. solani* AG-4, is one of the most serious diseases of pickling cucumber (*Cucumis sativus* L.) (8,12). Since belly rot affects fruit of all sizes, it directly reduces quality and marketable yield of the crop (27). Hand-culling diseased fruit increases harvest costs (23). Because *R. solani* AG-4 is pathogenic on many vegetables and other crops, rotation often is not an effective control practice. Moreover, legumes grown as cover crops increase belly rot on subsequent cucumber crops (26). Belly rot was reduced in experimental plots amended with *Trichoderma harzianum*, but high rates (200 kg/ha) were necessary to achieve significant control (17).

All commercially grown pickling cucumber cultivars are affected by belly rot. Although wild *Cucumis* spp. with very high levels of single-gene resistance have been identified in greenhouse screenings (5), the resistance appeared to be linked to fruit netting, a horticulturally undesirable characteristic (23). Results of greenhouse tests with detached fruit were not always correlated with results from field tests (34). Multiple-gene resistance has been identified, but its heritability is low (23), which has hindered breeding efforts. Thus, prospects are not promising for rapidly developing cultivars with increased levels of fruit resistance to *R. solani*.

Control of belly rot with protectant fungicides is hampered by difficulties in directing sprays to the infection court, i.e., the underside of the fruit. Fungicides are often applied to the soil surface before fruit develop to prevent belly rot. Although several fungicides effectively reduce belly rot (12,27), these often must be

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Corresponding author: A. P. Keinath
E-mail: tknth@clemson.edu

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Table 1. Mean maximum and minimum air temperatures, amount of sunshine, and monthly precipitation during solarization periods in 1992 to 1994

Month	1992				1993				1994			
	Max temp (C)[y]	Min temp (C)[y]	Sun (%)[z]	Rain (cm)[y]	Max temp (C)	Min temp (C)	Sun (%)	Rain (cm)	Max temp (C)	Min temp (C)	Sun (%)	Rain (cm)
July	33	24	76	13.2	35	24	73	8.9	32	23	71	27.2
August	31	23	67	28.8	33	23	76	14.5	31	22	73	7.8

[y] Temperatures and precipitation were recorded daily at the Coastal Research and Education Center, Charleston, South Carolina.
[z] Percentage of possible minutes of sunshine. National Weather Service, Charleston Airport, South Carolina. The airport is located 19 km from the experimental plots.

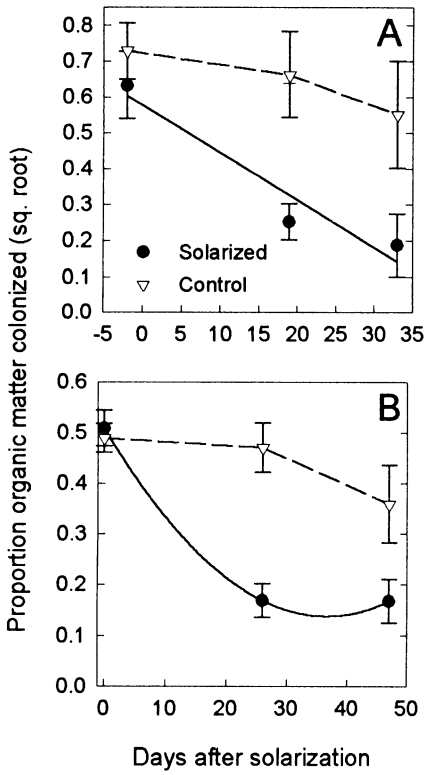

Fig. 1. Population dynamics of *Rhizoctonia solani* on organic matter in solarized and nonsolarized soil in **(A)** 1993 and **(B)** 1994. Organic matter was recovered from 400 g of soil at 0- to 10-cm depth and plated on ethanol-potassium nitrate agar. Populations declined significantly in solarized soil but not in nonsolarized soil. Error bars indicate one standard error of the mean.

applied at a high rate (22). Currently, the only fungicide registered for belly rot control is chlorothalonil at 6.9 kg/ha, a rate four times greater than the highest rate labeled for other cucurbit diseases. Deep-plowing infested soil or crop debris also reduced belly rot by physical displacement of the pathogen from the infection court, where the pathogen can grow toward or be splashed onto cucumber fruit (17). Additional management options are needed to supplement fungicide applications and tillage.

The effects of soil solarization on indigenous populations of *R. solani* and the level of disease that subsequently develops in solarized soil have not been examined. The objectives of this research were to monitor changes in populations of *R. solani* and other microorganisms in solarized and nonsolarized soil and to evaluate soil solarization as a management option for belly rot of cucumber. Preliminary reports have been published (15,16).

MATERIALS AND METHODS

Experimental plots. Plots were established at the Clemson University Coastal Research and Education Center in Charleston, South Carolina. The soil was a Yonges loamy fine sand (Typic Albaquult) in 1992 and 1994 and a Charleston loamy fine sand (Aquultic Hapludalf) in 1993, both naturally infested with *R. solani*. Fields used in 1992 and 1993 were cropped to tomato (*Lycopersicon esculentum* Mill. cv. Sunny) during the spring. Tomato transplants were set in the field on 23 March 1992 and 31 March 1993. Plants were not staked, to allow for maximum development of fruit rot to increase inoculum density of indigenous *R. solani*. Symptoms of Rhizoctonia soil rot or signs of the pathogen were observed on approximately 90 and 50% of the mature tomato fruit in 1992 and 1993, respectively. Plants and fruit were mowed on 10 July 1992 and 17 June 1993, and crop debris was disked 15 cm into the soil twice. The field used in 1994 was seeded in fall 1993 to crimson clover (*Trifolium incarnatum* L.) as a winter cover crop to increase inoculum density of *R. solani* (26). Clover was incorporated 10 cm into the soil by disking on 7 April 1994, and plots were kept fallow until solarization was begun. Fertilizer (90 kg/ha N, 40 kg/ha P, and 75 kg/ha K) and herbicide were applied prior to solarization in 1992 and immediately after solarization in 1993 and 1994. Bensulide (Prefar 4E, 6.7 kg/ha) and naptalam (Alanap 2E, 3.4 kg/ha) were applied preplant for weed control.

Plots were raised beds 15.2 m long and 0.9 m wide with a 9.1-m unplanted alley between ends of plots and 0.9 m between beds. In 1992 and 1993, the experimental design was a randomized complete block with six replications. Treatments were solarization, postplant fungicide application, and a nontreated control. In 1994, the experiment was a split-plot design, with inoculum levels as main plots and control methods as subplots. *R. solani* AG-4, isolate SP1 was obtained from a diseased spinach root in Bamberg County, South Carolina, December 1991, and stored on soil–wheat bran at –20°C (2). This isolate was pathogenic on cucumber, spinach, cabbage, and radish (*unpublished data*). Sclerotia were produced on autoclaved green beans (31). Sclerotia (710 to 1000 Tm diameter) were added or not added to whole plots at 14 sclerotia per kg of soil and incorporated with a hand-held rototiller to a depth of 15 cm.

Solarized plots were covered with a single layer of clear, 0.03-mm-thick, nonembossed, UV-stabilized, low-density polyethylene mulch (Edison Plastic Co., Lee Hall, VA). The mulch (1.37 m wide) was applied mechanically to plots and remained in place from 14 July to 31 August 1992 (48 days), 9 July to 12 August 1993 (34 days), and 14 July to 25 August 1994 (42 days). During 1992, soil temperatures were measured with a mercury thermometer weekly at 1400 h at 10- and 20-cm depths in all control and solarized plots. During 1993 and 1994, soil temperatures were measured and recorded every 10 min at 5, 10, 15, and 20 cm in control and solarized plots in two blocks with thermocouple probes (type T, model 105T) connected to a CR-10 micrologger (Campbell Scientific, Logan, UT). Maximum and minimum air temperatures and precipitation were recorded daily (Table 1).

After the plastic mulch was removed, pickling cucumber cv. Calypso was planted at 1 seed/15 cm on 1 September 1992, 13 August 1993, and 25 August 1994. On 15 September 1992, cucumber seedlings were transplanted into plots with poor emergence to give ca. 30 plants in the 4-m section of the plot to be harvested. When vines began to elongate (28 to 31 days after planting), chlorothalonil (Bravo 720, 6.9 kg/ha) was applied to chemical treatment plots with a tractor-mounted hydraulic sprayer on 2 October 1992 and 22 September 1994, and with a CO_2-powered backpack sprayer on 10 September 1993. Cucumbers were sidedressed with N (as ammonium nitrate) at 45 kg/ha on 7 and 13 September 1993 and 1994, respectively; plots were not sidedressed in 1992. Metalaxyl-chlorothalonil (Ridomil-Bravo 81W, 1.7 kg/ha) was applied on 28 September 1992 and 8 September 1993 to all plots to prevent development of downy mildew. Target spot was observed on foliage at the first harvest in 1993 and 1994. Benomyl (Benlate 50 WP, 0.28 kg/ha) and chlorothalonil (Bravo 720, 2.6 kg/ha) plus

Table 2. Population dynamics of fluorescent *Pseudomonas* spp. in solarized and nonsolarized soil

Treatment	1992			1993			1994		
	Initial[v]	Final	Decrease[w]	Initial	Final	Decrease	Initial	Final	Decrease
Control	3.78	3.47 NS[x,y]	0.31	3.77	2.07***	1.71	4.43	2.96**	1.47
Solarized	3.49	1.13****	2.36	4.17	0.00****	4.17	4.63	1.78****	2.85
LSD[z]	NS	1.53	1.75	NS	1.00	1.11	NS	NS	1.21
Alpha		0.01	0.01		0.01	0.01			0.05

[v] Log 10 (CFU) per g of oven-dry soil. Mean of 0- to 10-cm and 10- to 20-cm depths.
[w] Difference between initial and final population densities.
[x] *t* test for H_0: no change in population within treatment between initial and final samplings; **, $P \leq 0.01$; ***, $P \leq 0.001$; ****, $P \leq 0.0001$.
[y] NS = not significantly different.
[z] Fisher's protected least significant difference for treatment means within a column.

benomyl was applied on 21 and 30 September 1993, respectively; chlorothalonil (1.7 kg/ha) was applied on 22 September 1994, and chlorothalonil (1.7 kg/ha) plus benomyl (0.28 kg/ha) was applied on 17 October 1994 to all plots to prevent spread of target spot. Insects, primarily cucumber beetle and pickleworm, were controlled with applications of esfenvalerate (Asana XL, 0.056 kg/ha), permethrin (Ambush, 0.22 kg/ha), or methomyl (Lannate, 1.00 kg/ha) every 5 to 10 days after plants emerged.

Sampling. Ten soil cores (2.5 cm diameter) from 0- to 10-cm depth were collected from each solarized and control plot on 31 August 1992, 7 and 27 July and 10 August 1993, and 14 July and 9 and 30 August 1994. Cores were combined and thoroughly mixed. Organic matter was recovered from 400 g of soil by wet sieving through nested #18 (1-mm openings) and #60 (0.25-mm openings) mesh sieves and dried at ambient temperature (23 to 25°C) overnight. Organic matter retained on the #18 sieve was placed in 10 to 12 small heaps of equivalent size (32) on ethanol-potassium nitrate (EPN_2) medium (29), prepared with 2% ethanol (33) and without prochloraz in 1992 and 1993. After 1 to 3 days in the dark at 23 to 25°C, the total number of heaps with and without colonies of *R. solani* growing from them was recorded (32). Hyphae of randomly selected colonies were stained with 3% KOH and alkaline safranin O to determine the number of nuclei per cell (1). The anastomosis group of several isolates obtained in 1993 from soil and fruit was determined by pairing them with a known isolate of AG-4 (18). A most-probable-number procedure was used in 1992 and 1994 to determine CFU in organic matter retained on the #60 sieve (33). Organic matter was suspended in 50 ml of 0.25% water agar, and six 0.2-ml aliquots of four-fold dilutions were plated on EPN_2. Spots were examined for colonies of *R. solani* after 6 days in the dark at 23 to 25°C.

Population densities of selected microorganisms were determined before and after 6 weeks of solarization and compared to population densities in nonsolarized plots. Five 2.5-cm-diameter soil cores from 0- to 10-cm and 10- to 20-cm depths were collected from each plot on 16 July and 31 August 1992, 7 July and 12 August 1993, and 7 July and 26 August 1994 (noninfested plots). Composite soil samples for each plot were thoroughly mixed before 10.0-g subsamples were removed and added to 90 ml of sterile distilled water. Tenfold dilutions (10^{-2}, 10^{-3}, or 10^{-4}) were placed on S-1 medium and yeast-glucose agar to estimate populations of fluorescent pseudomonads (11) and thermotolerant fungi (25), respectively. After 2 days in the dark at 23 to 25°C, colonies of fluorescent pseudomonads were counted under long-wave UV light. Colonies of thermotolerant fungi were counted after 3 to 5 days at 40°C (9). All colony counts were expressed per gram of soil dried for 24 h at 100°C.

All cucumber fruit >5 cm long were harvested from a 4-m section of each plot on 15, 19, and 26 October and 4 November 1992; 20, 24, and 28 September and 4 October 1993; and 10, 18, and 26 October and 2 November 1994. Fruits were separated by diameter into the four commercial grades: <27 mm (No. 1), 27 to 38 mm (No. 2), 38.1 to 50.8 mm (No. 3), and >50.8 mm (No. 4). Numbers and weights of healthy and diseased fruits were determined for each grade. On diseased fruits, the percentage of the entire fruit surface area covered with lesions (disease severity) of belly rot or cottony leak was estimated visually. As a reference point, the underside of the fruit was considered to be 30% of the entire fruit surface area (34). Diseased fruit were sampled from most harvests in each year by one of two methods. Some fruit were placed in a moist chamber overnight. Mycelium that grew from lesions was stained with safranin O or cotton blue in lactophenol and examined at 400× to verify the presence of *R. solani* or *Pythium* spp. Pieces from lesions on other fruits were surface-disinfested in 0.5% sodium hypochlorite and placed on quarter-strength potato-dextrose agar to recover *R. solani* and on pimarcin-vancomycin-polymixin medium (30) supplemented with 50 mg of penicillin per liter (6) in 1992 and water agar in 1993 and 1994 to recover *Pythium*.

The price per 45.4 kg of fruit in 1992 to 1994 was $16.00 for No. 1, $8.00 for No. 2, and $4.80 for No. 3 fruit. Because growers are not paid for oversized fruit (size class 4), these fruit were excluded from all analyses. Treatment costs were

Table 3. Populations of thermotolerant fungi in soils solarized or not solarized

Treatment	1992[w]	1993	1994		
			Initial	Final	Difference[x]
Control	0.72	3.56	1.37	1.36	–0.014
Solarized	1.85	3.76	0.88	1.47	0.585
LSD[y]	0.73	NS[z]	NS	NS	0.56
Alpha	0.01				0.05

[w] Log 10 (CFU) per g of oven-dry soil. Mean of 0- to 10-cm and 10- to 20-cm depths.
[x] Difference between initial and final population densities.
[y] Fisher's protected least significant difference for treatment means within a column.
[z] Not significantly different.

Table 4. Populations of thermotolerant *Penicillium* spp. in soils solarized or not solarized

Treatment	1992		1993		1994	
	Final[w]	Percent[x]	Final	Percent	Final	Percent
Control	0.42	48.1	1.40	0.85	1.04	47.9
Solarized	1.81	91.5	2.56	17.9	1.29	70.9
LSD[y]	0.64	24.4	1.09	6.0	NS[z]	19.6
Alpha	0.01	0.01	0.05	0.01		0.05

[w] Log 10 (CFU) per g of oven-dry soil. Mean of 0- to 10-cm and 10- to 20-cm depths.
[x] Percent of all thermotolerant fungi recovered.
[y] Fisher's protected least significant difference for treatment means within a column.
[z] Not significantly different.

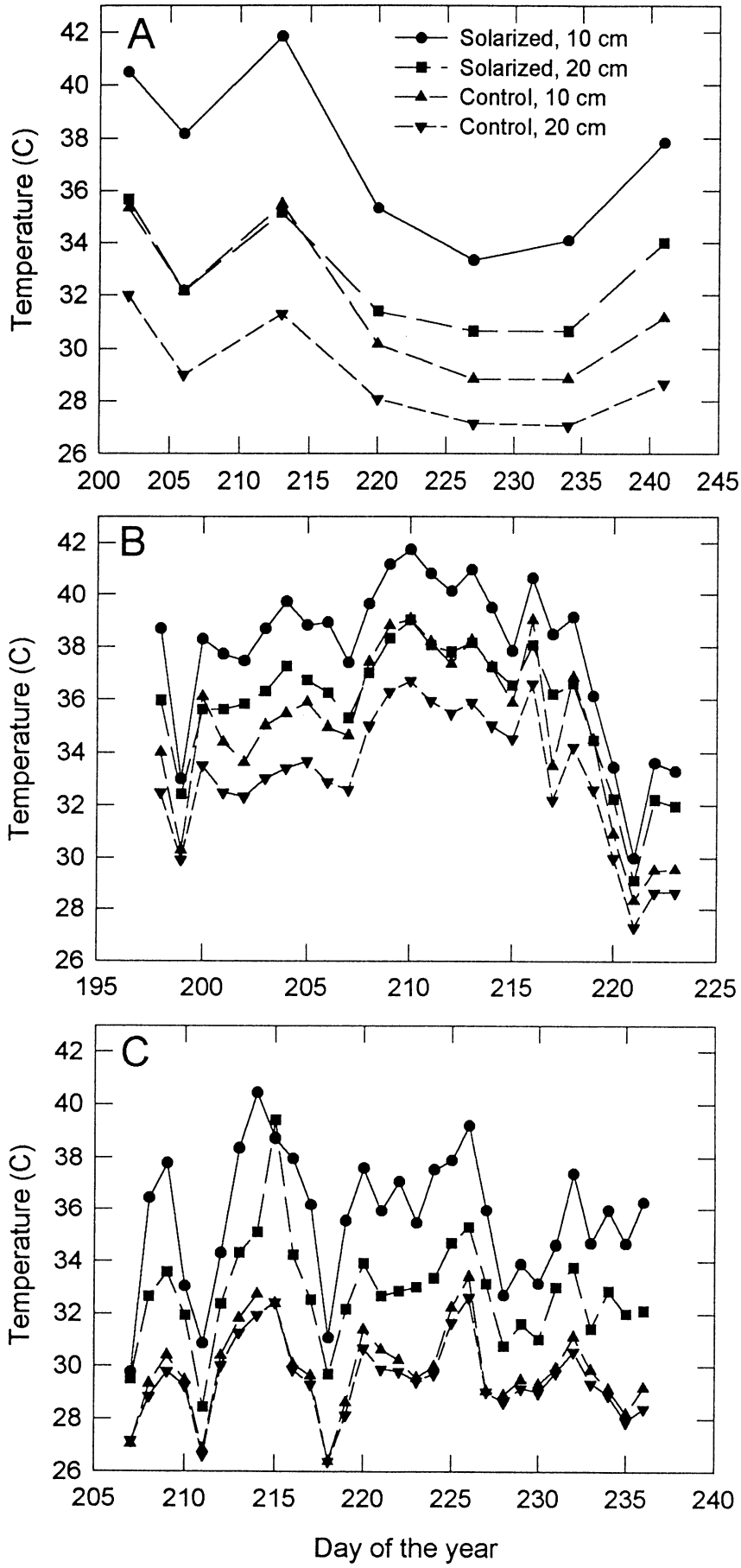

Fig. 2. Soil temperatures recorded at 1400 h in plots solarized or not solarized for 5 to 6 weeks during July and August (**A**) 1992, (**B**) 1993, and (**C**) 1994. Temperatures were measured at the 10-cm depth in six replicate plots once per week in 1992 and in two replicate plots every 10 min in 1993 and 1994.

estimated to be $0 for no treatment, $461/ha for solarization ($422 for clear polyethylene + $25 for operation of the plastic layer + $13.60 for labor), and $133/ha for fungicide application ($126 for chlorothalonil + $1.70 for operation of the sprayer + $1.10 for labor).

Statistical analysis. Analysis of variance was performed with PROC GLM of SAS (SAS Institute, Cary, NC; release 6.04 for personal computer). All data sets were tested for equality of variance and normality before analysis, and transformed when necessary. Multivariate analysis of variance was used to compare disease and yield data among the different fruit size classes. Repeated measures analysis of variance was used to compare disease and yield data from the different harvests within years. When size and harvest date had no effect on treatment, data were pooled across size classes and harvests. Treatment means were compared with the Waller-Duncan *k*-ratio *t* test (three means) or Fisher's protected least significant difference (two means).

RESULTS

In 1992, the percentage of organic matter >1 mm diameter colonized by *R. solani* was reduced (F significant at $P = 0.04$) from 22.7% ± 7.7% (standard error) in nonsolarized soil to 0.90% ± 0.70% in soil solarized for 6 weeks. In 1993 and 1994, percent organic matter colonized by *R. solani* decreased significantly over time in solarized soil but not in nonsolarized soil (Fig. 1). In 1993, the decrease was linear ($y = 0.58 - 0.013x$, $P = 0.0008$, $R^2 = 0.51$, y = square root of percent organic matter colonized and x = days after solarization was begun), whereas in 1994, the decrease was nonlinear ($y = 0.51 - 0.020x + 0.00028x^2$, $P = 0.0001$, $R^2 = 0.63$). After 32 days of solarization, the percentage of organic matter with one or more colonies of *R. solani* was 2.5% in 1993 and 2.7% in 1994. In both years, percent colonized organic matter was not significantly different between solarized and control plots when the experiments were begun. Percent organic matter colonized by *R. solani* was lower in solarized soil than in nonsolarized soil at 19 days after solarization was begun in 1993 and at 26 and 47 days in 1994 (F significant at $P = 0.01$, 0.003, and 0.025, respectively). After solarization, recovery of *R. solani* from organic matter was reduced 96, 83, and 89% in 1992, 1993, and 1994, respectively, compared with nonsolarized soil. There was no difference in recovery of *R. solani* between infested and noninfested plots in 1994 (data not shown). Only one colony of *R. solani* (equivalent to 3.5 CFU per 100 g of soil) was recovered from small organic debris <1 mm but >0.25 mm in 1992; no colonies were recovered in 1994. In 1993, 100% of the *Rhizoctonia* colonies examined were multinucleate (*R. solani*) (N = 26 and 21

Table 5. Soil temperatures (℃) in solarized and nonsolarized plots during July and August 1993 and 1994

Year	Depth (cm)	Nonsolarized Mean[y]	Nonsolarized Max mean[z]	Nonsolarized Min mean	Nonsolarized Cum h >40°C	Solarized Mean	Solarized Max mean	Solarized Min mean	Solarized Cum h >40°C
1993	5	31.4	39.6	26.3	53.0	35.2	46.4	28.2	148.5
	10	31.2	37.2	27.1	16.5	34.7	40.7	30.2	90.5
	15	31.2	36.9	27.4	17.5	34.7	40.0	30.8	75.0
	20	31.1	35.5	28.0	7.0	34.6	38.9	30.9	43.5
1994	5	27.8	33.9	23.9	0	32.1	40.0	26.8	40
	10	27.6	37.2	24.8	0	32.2	38.2	27.7	22
	15	27.7	31.5	24.9	0	32.5	37.6	28.6	10
	20	27.7	31.2	25.0	0	32.6	38.8	28.0	31

[y] Mean temperatures were calculated from mean hourly temperatures, which were the means of readings taken every 10 min.
[z] Mean maximum and minimum temperatures are the means of the daily absolute maximum or minimum temperatures recorded.

for samplings on 27 July and 10 August, respectively); seven of 11 colonies tested were AG-4. In 1994, 93 and 90% of the colonies were multinucleate (N = 58 and 20 for samplings on 9 and 30 August, respectively) and the remainder were binucleate (*Rhizoctonia* spp.).

Population densities of fluorescent *Pseudomonas* spp. declined significantly (*t* test, $P = 0.0001$) in solarized soil during the solarization period in all 3 years (Table 2). The predominant colony type in each year produced a yellow-green fluorescent pigment. After 5 weeks of solarization in 1993, the population density of fluorescent pseudomonads was below the detection threshold, <100 CFU/g of soil. Population densities after solarization were significantly lower in solarized soil than in control soil in 1992 and 1993. Populations also declined significantly in control soil in 1993 and 1994, but the difference between pre- and post-solarization populations was always significantly greater in solarized than in nonsolarized soil (Table 2). In 1992, average log population densities after solarization were lower at 0 to 10 cm, 2.65 ± 0.37, than at 10 to 20 cm, 3.28 ± 0.26 (F significant at $P = 0.05$); there was no effect of depth in the other 2 years.

In 1992 and 1994, but not in 1993, populations of thermotolerant fungi, which grew at 40°C, increased in solarized but not in nonsolarized soil. Population densities of thermotolerant fungi were 10-fold higher in treated plots after solarization in 1992 than in control plots (Table 3). In 1994, the difference between pre- and post-solarization populations was significantly greater in solarized than in nonsolarized soil. In 1992 and 1994, most of the thermotolerant fungi recovered from solarized soil were thermotolerant *Penicillium* spp. (Table 4). The percentage of *Penicillium* spp. among all thermotolerant fungi was significantly greater in solarized than in nonsolarized plots each year. Postsolarization population densities of this group were 10-fold greater in solarized than in nonsolarized plots in 1992 and 1993, but not in 1994 (Table 4).

In all 3 years, soil temperatures in solarized plots were greater than temperatures at the same depths in nonsolarized plots (Fig. 2). In 1992, the average soil temperature at 1400 h at the 10-cm depth in solarized plots, 37.2°C, was significantly greater than that in nonsolarized plots, 31.7°C. In 1993 and 1994, more hours of temperatures >40°C were recorded in solarized than in nonsolarized plots at all depths (Table 5). Average maximum temperatures in solarized plots were 6.8°C greater at 5 cm and 3.3°C greater at 10 to 20 cm than in nonsolarized plots in 1993; 6.1°C greater at 5 cm but 6.9°C greater at 10 to 20 cm in 1994. Average minimum temperatures were approximately 3°C lower in nonsolarized than in solarized soil at all depths both years.

Disease incidence and severity were moderate but representative of conditions in growers' fields. Incidence of cottony leak, caused by *Pythium* spp., was 4 to 9% at the second and fourth harvests in 1992 and at the first three harvests in 1994; no cottony leak was detected in 1993. Disease incidence, based on the number of fruits with belly rot or cottony leak, was reduced 57% by solarization and 74% by chlorothalonil application when compared with the control in 1993 (treatment F significant at $P = 0.003$) but not in 1992 (Table 6). In 1994, both solarization and chlorothalonil were effective in noninfested plots, but only chlorothalonil reduced the percentage of diseased fruit in the infested plots (Table 7). Percentage of the entire fruit surface covered with belly rot lesions (disease severity) was 52% lower in solarized plots than in control plots in 1992 (treatment F significant at $P = 0.05$) (Table 6) and 66% lower in 1994 (F significant at $P = 0.03$) (Table 7). Chlorothalonil reduced belly rot severity in 1993 (treatment F significant at $P = 0.06$) and 1994 but not in 1992. There was no consistent effect of harvest date on disease or yield.

The weight of healthy fruit of sizes No. 1, 2, and 3 did not differ among treatments in any year (Tables 6 and 7). Treatment had no effect on distribution of fruit among the size classes (*unpublished data*). In 1994, the value of the healthy fruit was $467/ha greater in the solarization treatment (F significant at $P = 0.04$) than in the other two treatments (Table 7), but value did not differ among treatments in 1992 and 1993 (Table 6). When the costs of solarization ($461/ha in 1994) and chlorothalonil application ($133/ha in 1994)

Table 6. Incidence and severity of belly rot and yield and value of pickling cucumber in plots solarized before planting, treated with chlorothalonil at vine elongation, or not treated

Year	Treatment	Incidence (%)[u]	Severity (%)[v]	Yield (kg/ha)[w]	Value ($/ha)[x]
1992	Control	15.7[y]	10.1 a	6,843	1,121
	Solarization	14.9	4.8 b	9,803	1,618
	Chlorothalonil	14.1	7.1 ab	7,203	1,199
		NS[z]		NS	NS
1993	Control	10.6 a	15.0 a	7,399	1,106
	Solarization	4.6 b	9.6 ab	6,432	958
	Chlorothalonil	2.8 b	4.0 b	7,145	1,055
				NS	NS

[u] Disease incidence is the number of diseased fruit/total number fruit × 100. Data were transformed to arcsine square roots before analysis in 1993; values shown are back-transformed means.
[v] Disease severity is the percentage of the entire fruit surface area covered with belly rot lesions on diseased fruits.
[w] Sum of the weights of healthy No. 1, 2, and 3 fruit (i.e., free of belly rot and cottony leak lesions) over four harvests.
[x] Values were calculated from yield, where price per 45.4 kg was $16.00 for No. 1, $8.00 for No. 2, and $4.80 for No. 3 fruit.
[y] Values within a column by year followed by the same letter are not significantly different, Waller-Duncan k-ratio t test, $k = 100$ (approximates $P = 0.05$).
[z] No significant differences among treatments.

were subtracted from the value of the pickles produced in each replication of these treatments, the resulting mean return did not differ among treatments (Table 7).

DISCUSSION

In all 3 years of field tests, percent organic matter colonized by *R. solani* was reduced significantly in solarized soil when compared with nonsolarized soil. On fragments of organic matter >1 mm diameter, colonization by *R. solani* was reduced by an average of 86% in solarized plots at 0 to 10 cm. In California, *R. solani* at 0 to 15 cm was not detected in solarized soil, while nonsolarized soil contained 4 CFU per 100 g (20). On organic debris >0.25 mm diameter, *R. solani* was only recovered at the detection threshold in one of 12 plots in 1 year. It is likely that fewer hyphae are present on small fragments than on larger pieces of organic matter. In addition, small fragments would be likely to decompose faster than larger pieces in solarized soil (13). Therefore, *R. solani* may be more vulnerable to elevated soil temperatures when it occupies a small fragment of debris rather than a larger piece of organic matter.

R. solani was reduced by 83 and 86% in solarized plots when the cumulative hours >40°C were 148.5 and 40 in 1993 and 1994, respectively. In vitro, viability of *R. solani* was reduced by 90% after 336 h at a constant temperature of 39.1°C (19). Sublethal heating at temperatures <40°C, which can weaken fungal propagules and structures (13), may have contributed to the more rapid decrease of *R. solani* in solarized soil. Reducing *R. solani* more than 86% with solarization may require higher soil temperatures than recorded in this study. In 1994, the most rapid decrease in recovery of *R. solani* occurred between 1 and 26 days after solarization began, and in 1993 populations were significantly reduced 19 days after solarization was initiated. Based on these results, a 4-wk solarization period might be able to reduce *R. solani* to levels similar to those achieved during 6 wk. If, because of the time required for a spring crop to mature, 6 weeks of solarization was not feasible, 4 weeks of solarization before planting a fall crop still would reduce the population of *R. solani* significantly.

Thermotolerant fungi, including thermotolerant *Penicillium* spp., and fluorescent *Pseudomonas* spp. responded to soil solarization as expected based on results from other field studies: thermotolerant fungi generally increased and fluorescent pseudomonads decreased (9,21,25). Changes in populations of saprophytic microorganisms, as well as reductions in the population of *R. solani*, indicate that solarization may be a useful component of biologically based control systems for soilborne pathogens in the southeastern United States. Maximum soil temperatures in solarized plots in coastal South Carolina generally were similar to those reported in solarized soil in other locations in the southeastern United States, but hours of cumulative temperatures >40°C were lower (3,21). Possibly, soil cooled more rapidly than at other locations. Combinations of solarization with organic amendments such as cruciferous crop residues or composts, which have been used to enhance the effectiveness of solar heating at suboptimal temperatures (10), should be evaluated for control of *R. solani*.

Incidence and severity of belly rot were reduced by 52 to 66% in solarized soil in the 3 years of this study. This percent reduction was less than the average 86% reduction in populations of *R. solani* in solarized soil. Chlorothalonil applications reduced belly rot incidence by 50 to 74%, which is very similar to previously published results (27). In that study, CFU of *R. solani* also were reduced (90%) to a greater extent than disease incidence in surface soil treated with chlorothalonil (27). Chlorothalonil, benomyl, and metalaxyl-chlorothalonil applied to plots to control foliar diseases had no observable effect on belly rot. Chlorothalonil was used at only one-sixth to one-fourth of the rate needed to reduce belly rot, and benomyl and metalaxyl are ineffective against this disease (22). Fungicides were applied to plots after a dense leaf canopy prevented most of the material from contacting the soil. For this reason, manufacturers of chlorothalonil recommend application no later than vine elongation for control of belly rot.

Although solarization reduced belly rot, it had no consistent effect on marketable yield of pickling cucumber. Solarization has increased shoot growth of certain crops, such as tomato (9,21), eggplant (14), and cotton (9), and yield and average fruit weight of eggplant (14), but tomato fruit yield was not increased in solarized plots in which viability of *S. rolfsii* sclerotia was reduced (21). Likewise, a significant beneficial effect of solarization on cucumber fruit production was not observed in this study. However, the effect of *R. solani* on the yield of cucumber fruit is less damaging than the effects of other soilborne pathogens such as *S. rolfsii* or *Verticillium dahliae*, which infect or kill entire mature plants. Consequently, the benefits of solarization on yield also are less apparent (13).

Currently, solarization is more costly to apply in pickle production than chemical control, which would limit its adoption by growers. Although the price a producer would have received for fruit harvested from the solarization treatment was significantly greater than no treatment in 1 year, the economic return, after the cost of clear polyethylene mulch and its application was deducted, was not significantly greater than in the nontreated control in any year. However, a less expensive mulch would bring the cost of solarization closer to that of chemical application. A consistent yield increase in solarized soil also would help to offset the cost of the mulch input. In addition, the economic benefits of solarization could be greater in soils more heavily infested with *R. solani* than those used in this study, if similar reductions in disease were achieved (35).

Solarization could be combined with a fungicide application for integrated control of cucumber belly rot. Although not specifically tested in this study, such a combination treatment likely would be more effective than applying each treatment

Table 7. Incidence and severity of belly rot and yield, value, and economic return of pickling cucumber in plots solarized before planting, treated with chlorothalonil at vine elongation, or not treated in 1994

Treatment	Incidence (%)[s] Noninfested soil	Incidence (%)[s] Infested soil	Severity (%)[t]	Yield (kg/ha)[u]	Value ($/ha)[v]	Return ($/ha)[w]
Control	7.4 a[x]	5.2 a	12.9 a[y]	9,652[y]	1,477 b[y]	1,477[y]
Solarization	3.2 b	6.2 a	4.4 b	11,917	1,944 a	1,483
Chlorothalonil	3.7 b	2.3 b	4.1 b	9,699	1,462 b	1,329
				NS[z]		NS

[s] Disease incidence is the number of diseased fruit/total number fruit × 100. Data were transformed to square roots for analysis; values shown are back-transformed means. Treatment × inoculum interaction was significant ($P = 0.05$).

[t] Disease severity is the percentage of the entire fruit surface area covered with belly rot lesions on diseased fruits. Data were transformed to square roots before analysis; values shown are back-transformed means.

[u] Sum of the weights of healthy No. 1, 2, and 3 fruit (i.e., free of belly rot and cottony leak lesions) over four harvests.

[v] Values were calculated from the yield, where price per 45.4 kg was $16.00 for No. 1, $8.00 for No. 2, and $4.80 for No. 3 fruit.

[w] Return = value – cost. Treatment costs were estimated to be $0 for control, $461/ha for solarization, and $133/ha for chlorothalonil (Bravo 720) application.

[x] Values within a column followed by the same letter are not significantly different, Waller-Duncan *k*-ratio *t* test, $k = 100$ (approximates $P = 0.05$).

[y] Values were averaged across inoculum levels (no significant treatment × inoculum interactions).

[z] No significant differences among treatments.

separately. Solarization could be utilized to reduce the preplant inoculum density of *R. solani*, then followed by a single application of chlorothalonil, possibly at a lower rate than currently is recommended. A combination of solarization and chlorothalonil would not be cost effective on pickling cucumber. However, the combination treatment may be applicable to slicing cucumber and processing tomato for control of belly rot and Rhizoctonia soil rot, respectively.

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