Soil Solarization: Effects on Verticillium Wilt of Cotton and Soilborne Populations of *Verticillium dahliae, Pythium* spp., *Rhizoctonia solani,* and *Thielaviopsis basicola*

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ABSTRACT

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In field tests during the summers of 1977–1979, solarization of soil by covering it with transparent polyethylene tarps was examined for effectiveness in controlling soilborne pathogens. Propagules of *Verticillium dahliae, Pythium* spp., *Thielaviopsis basicola,* and *Rhizoctonia solani* were greatly reduced or completely eliminated 0–46 cm in soil tarped for 14–66 days. Higher soil temperatures and a more rapid decline in pathogen populations occurred in soils irrigated after placement of tarps than in those preirrigated and then tarped. Tarps 25 μm (1-mil) thick were more effective in heating soils and in killing soilborne fungi than were 100-μm (4-mil) tarps. The mycorrhizal fungus *Glomus fasciculatus* survived tarping treatments as measured by colonization of cotton (*Gossypium hirsutum*) roots. Incidence of Verticiilium wilt was reduced and cotton yields were increased in plants of cultivars Acala SJ-2 and SJ-5 planted in tarped compared with nontarped soil.

Additional key words: solar heating, mulching, thermal killing.

Among the soilborne pathogens of cotton (*Gossypium hirsutum* L.) in California, *Verticillium dahliae* Kleb., *Pythium ultimum* Trow, *Rhizoctonia solani* Kuehn, and *Thielaviopsis basicola* (Berk. & Br.) Ferr., cause the main disease problems (7). At present, controls for *P. ultimum* and *R. solani* depend on chemical seed treatments and (to some extent) on supplemental fungicides. No satisfactory control is available for *T. basicola. V. dahliae* is currently managed by fertilization and irrigation practices, crop rotation, and use of tolerant Acala cotton cultivars. However, highly virulent strains of *V. dahliae* are widespread and frequently cause significant loss of lint yield in Acala cotton plantings.

Katan et al (16) in 1976 reported control of *V. dahliae* and several other soilborne plant pathogens in Israel by covering a drip-irrigated soil with transparent polyethylene plastic for several weeks during the hot summer months thereby increasing soil temperatures. Preliminary experiments at Davis, CA, during 1976 showed that furrow irrigations under the plastic could substitute for drip irrigation and that tarping of dry soil was not successful in reducing soil populations of *V. dahliae* (21,22). Plastic tarps traditionally were used to heat soils in the spring or as a mulching agent to prevent water loss and to reduce weed growth. However, only recently have clear polyethylene tarps been used as a soil disinfestation method to heat noncropped soil to temperatures lethal to certain soilborne organisms (12,15,16).

The main objective of this study was to determine whether soil solarization, a process that utilizes the sun to heat soils under transparent plastic tarps to temperatures lethal to soilborne organisms, would control Verticillium wilt in cotton. Populations of *V. dahliae, Pythium* spp., *R. solani, T. basicola,* and mycorrhizal fungi also were monitored. The effects of irrigation sequence, thickness of plastic, and length of treatment on populations of the fungi also were determined. Preliminary reports on part of this work have appeared (22–24).

MATERIALS AND METHODS

Field experiments, 1977. Solarization tests were located at the USDA Cotton Research Station, Shafter, CA. The soil type was Hesperia fine sandy loam. High natural soil populations of *V. dahliae* (51 propagules per gram of soil) and *Pythium* spp. (200 propagules per gram of soil) were present within the upper 30 cm. *R. solani* (3.9 propagules per 100 g of soil) was also present in the upper 15 cm together with low populations of *T. basicola* (>10 propagules per gram of soil). In previous years, this site had a high incidence of Verticillium wilt in cotton crops.

Individual plots 3.4 × 10.7 m were arranged in a randomized

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complete block design consisting of five treatments (Table 1), each with six replications. Solarized plots were covered with transparent polyethylene plastic either 25 μm (P-25) or 100 μm (P-100) thick. All field plots, including nontarped areas, were preirrigated with 5 to 10 cm/ha of water 1 wk before the tarps were placed on the soil. The soil was disked and floated to provide a uniform surface, and tarps were applied by machine on 29 June 1977. Care was taken to minimize the distance between the tarps and soil to prevent air pockets that retard the soil heating process. The next day all treatments, including those under the plastic, were flood irrigated with 5–10 cm/ha of water. Tracks left by the caterpillar tractor while applying the plastic provided shallow furrows that helped to distribute water under the plastic. Thereafter, each plot was irrigated at the same rate every 2–3 wk until the plastic was removed.

Soil temperatures were monitored throughout the experiments at depths of 5, 15, 30, and 46 cm in one replication of nontarped, P-25 covered, and P-100 covered soil.

Soil samples were collected from nontarped and tarped areas on the day the tarps were removed. Soil samples consisted of 10–12 cores (30 × 2.5 cm) collected from each plot. The soil in each core was divided into the upper and lower 15 cm. Core halves were bulked, and mixed for each pathogen assay. Approximately 4 L of soil from the 0–15, 15–30, and 30–46 cm depths also were collected from three nontarped and three tarped (58 days) plots to be assayed for mycorrhizal fungi.

The effectiveness of soil solarization below 30 cm also was monitored by placing 100-cm^3 samples of field soil containing *V. dahliae* and *Pythium* spp. propagules, enclosed in nylon mesh bags, at a depth of 46 cm in three plots of each treatment. Because low populations ($>$10 propagules per gram) of *T. basicola* were present in experimental plots, soil containing high populations of *T. basicola* (75 propagules per gram of soil) was placed in nylon mesh bags and buried at depths of 15, 30, and 46 cm, also in three plots of each treatment. After removal of the tarps, the buried samples were retrieved and assayed for the respective fungi.

Safflower (*Carthamus tinctorius* L. 'Oleic Leed') was planted on 28 July 1977 in rows 1 m apart in all plots except those covered for 58 days. One hundred plants in each plot were rated for foliar symptoms of Verticillium wilt on 3 November 1978. To obtain seed yields, all plants in a 4-m section of row in the center of each plot were collected and passed through a Vogel Thrasher. Seed was air-dried and yields were converted to kilograms per hectare.

In the next growing season Acala SJ-2 cotton was planted in all plots to test the long-term effects of soil solarization. Soil samples were collected from the upper 30 cm in early May 1978. On 12 September 1978 cotton plants within a 4-m section of the center row of each plot were rated for foliar symptoms of Verticillium wilt. Seed cotton was hand-picked from the same 4-m sections approximately 2 mo later.

Experiments also were made at Davis, CA, where the natural soil population of *V. dahliae* averaged 168 propagules per gram of soil in the top 30 cm and 35 propagules per gram of soil at 30–46 cm. Individual plots 4.3 × 9.2 m were arranged in a randomized complete block design consisting of three treatments with three replications: nontarped, tarped with P-100, and tarped with P-100 and irrigated once under the plastic. All plots were preirrigated, disked 1 wk later, and then plastic tarps were laid by hand. The tarp edges were buried around the plot to firmly anchor the plastic, which remained in place for 66 days.

Maximum soil temperatures were measured for each treatment at depths of 5, 15, and 30 cm. Soil samples were collected for all treatments from 0–15, 15–30, and 30–46 cm depths after 2 wk of treatment and again when tarps were removed after 9 wk. Soil samples also were collected from the same depths when tarps were removed, and assayed for the presence of mycorrhizal fungi.

In the following growing season, Acala SJ-2 cotton was planted in rows 76 cm apart. An average of 31 plants was examined for foliar symptoms of Verticillium wilt on 21 September 1978 in a 3-m section of the center two rows of each plot. At the end of the season, all bolls were hand-collected from these plants and oven-dried at 60 C. Seed cotton was then collected, weighed, and yields were converted to kg/ha.

Field experiments 1978. One experiment was located at Five Points, CA. The soil type was Panoche clay loam, which contained approximately 59 propagules of *V. dahliae* per gram of soil in the upper 30 cm. The second field site was near Mettler, CA. The soil type was San Emigdio sandy clay loam and contained approximately 36 propagules of *V. dahliae* per gram in the upper 30 cm.

At Five Points, two treatments with six replications each were randomized in a complete block design. Individual plots 8 × 20 m were either left nontarped or were tarped with clear 25-μm polyethylene plastic (P-25). Two strips of plastic each 3.4 × 20 m were applied approximately 75 cm apart by machine in tarped plots on 15 June 1978. Tarped areas were flood irrigated underneath the plastic the next day with approximately 5–10 cm/ha of water. Soil samples were collected from nontarped and tarped areas after the tarps were removed 5 wk later. Soil samples also were collected from the center of the 75 cm nontarped space between the plastic strips. To determine the effect of an intermediate crop, *Sorghum bicolor* (L.) Moench. 'Northrup King 115' was planted in all plots 1 wk after the plastic was removed. Sorghum seed was harvested in late November.

During the 1979 growing season, Acala SJ-2 cotton was planted in rows 1 m apart. On 14 September 1979 plants in four 6-m sections of row were examined for foliar symptoms of Verticillium wilt. At the end of the season, seed cotton was machine harvested from approximately 80 m of row within each plot.

At the Mettler site two treatments each with six replications were incorporated in a randomized complete block design. Individual plots were 8 × 30 m. P-25 was applied on 10 August 1978 in strips in the same manner as described for the Five Points experiment. Tarped plots were flood irrigated underneath the plastic the next day with approximately 5–10 cm/ha of water. Tarps were removed 32 days later. Soil samples (30-cm cores) were collected before placement and after removal of the tarps. Soil samples were also collected from the nontarped space between the plastic strips.

TABLE 1. Effect of soil solarization at Shafter, CA, on soil populations of *Verticillium dahliae*, incidence of Verticillium wilt, safflower seed yields during 1977, and lint yields of cotton during 1978

	Safflower - 1977			Cotton - 1978		
Treatment[x]	*V. dahliae* propagules/g (0–30 cm)[y]	% Disease (foliar symptoms) (3 Nov 1977)	Seed yield (kg/ha)	*V. dahliae* propagules/g (0–30 cm)[z]	% Disease (foliar symptoms) (12 Sept 1978)	Lint yield (kg/ha)
Nontarped	46.5 a	42 a	269 a	42.0 a	77 a	865 a
Tarped P-25 14 days	1.5 b	3 b	573 b	7.3 b	60 ab	796 a
Tarped P-25 28 days	0.2 b	0 b	536 b	5.3 b	36 b	838 a
Tarped P-100 28 days	0.2 b	2 b	573 b	8.0 b	42 b	883 a
Tarped P-100 58 days	0.0 b	...	...	1.3 b	3 c	842 a

[x]P-25 (clear 25-μm polyethylene plastic) and P-100 (clear 100-μm polyethylene plastic) were placed on the soil on June 29, 1977. Safflower cultivar Oleic Leed was planted on July 28, 1977, followed by cotton (Acala SJ-2) in 1978. Values within columns followed by the same letter are not significantly different (Duncan's multiple range test, $P = 0.01$).

[y]Values are condensed from Table 3.

[z]Soil samples were collected 5 May 1978.

Acala SJ-5 cotton, which exhibits field tolerance to Verticillium wilt in California's San Joaquin Valley, was planted in 1979 on rows 1 m apart. Fifty plants within each plot were rated for foliar symptoms of Verticillium wilt on 12 September 1979. Seed cotton was hand-picked from two 4-m sections of row within each plot.

Throughout both of the above experiments, soil temperatures at depths of 15, 30, and 46 cm were continuously recorded in one tarped and one nontarped plot.

Soil sampling and assays for plant pathogenic fungi. Soil samples were gathered from various depths in cores 2.5 cm in diameter. Ten to 12 cores were randomly collected and bulked for each sample. The inoculum density of *V. dahliae* was assayed by the technique of Butterfield and DeVay (6). Soil samples were air-dried at room temperature for 6 wk and milled for 20 min in a 5-L revolving jar mill. Five 100-mg samples of soil were spread on a partially selective sodium polypectate medium with an Anderson Air Sampler (Anderson Samplers Inc., Atlanta, GA 30336). Plates were incubated at room temperature for 2 wk, rinsed with water, and examined with the aid of a stereo dissecting microscope for microsclerotial colonies of *V. dahliae*. The method is highly sensitive and can detect as few as two propagules per gram of soil. A similar technique was used to determine soil population densities of *Pythium* spp. (9); 10 to 100 mg amounts of soil were spread with an Anderson Air Sampler onto MVPM media (19). Plates were incubated at 23 C for 48–72 hr and visible colonies of *Pythium* spp. were counted. Soil inoculum densities of *R. solani* were determined by using the technique of Weinhold (28). Concentrations of *T. basicola* were assayed by a modification of the carrot-baiting technique of Yarwood (29). Twenty fresh carrot disks approximately 6-mm thick were each covered with approximately 0.011 cm^3 of moist soil that was spread with a spatula to form a layer over each carrot piece. Treated carrot slices were placed in sterile 9-cm-diameter petri plates that contained a sheet of sterile Whatman No. 2 filter paper and 5 ml of 50 ppm aqueous streptomycin sulfate. The treated carrots were incubated at room temperature for 3 days. The soil was then washed away and the carrot pieces were incubated for an additional 4 days at room temperature. Carrot disks were then rated for the presence or absence of *T. basicola*. The percentage of carrot disks colonized gave a semiquantitative estimate of *T. basicola* populations.

TABLE 2. Effect of soil solarization on soil temperatures at various soil depths during experiments conducted in 1977 and 1978 at four locations in California

Location, date, and treatment[a]	Maximum soil temperatures (C) 5 cm	15 cm	30 cm	46 cm
Shafter, CA - 1977				
29 June–26 July				
Nontarped	46	39	32	30
Tarped P-25	60	50	41	39
Tarped P-100	57	48	40	38
Davis, CA - 1977				
19 July–21 September				
Nontarped	42	32	27	···
PI + tarped P-100	53	44	38	···
PI + tarped P-100 + IU	55	45	39	···
Five Points, CA - 1978				
15 June–13 July				
Nontarped	···	35	31	29
Tarped P-25	···	47	40	37
Mettler, CA - 1978				
10 August–2 September				
Nontarped	···	38	35	35
Tarped P-25	···	47	40	38

[a]P-25 = clear 25-μm polyethylene plastic. P-100 = clear 100-μm polyethylene plastic. PI = Preirrigation 1 wk before the soil was tarped with plastic. IU = a single flood irrigation under the plastic.

Identification of *Pythium* species. Soil was air-dried and plated as previously described for *Pythium* spp. Fifty of the resulting colonies were isolated for each treatment. Each isolate was placed in a petri dish that contained a 1-cm-diameter disk of lima bean agar embedded in water agar. Based on sexual and asexual reproductive structures produced, the isolates were identified by using the key of Middleton (18).

Soil assay for mycorrhizae in cotton roots. Three replicates of the tested soil were placed in 14-cm-diameter greenhouse pots and planted with Acala SJ-2 cotton. Plants were thinned to one per pot and after 2 mo soil particles were rinsed from the root systems and the roots were then cut into 5-mm segments. Rootlets were stained by using the technique of Bird et al (5). Thirty stained root segments per plant were examined for mycorrhizae. A total of 90 rootlets were examined for each soil sample.

RESULTS

Effects on soil temperatures. At the Shafter location, soil covered with P-25 reached higher maximal temperatures (1–3 C) than that covered with P-100 at all depths tested (Table 2). Soil temperatures

TABLE 3. Effect of soil solarization and irrigation on the viability of plant pathogens in naturally infested soils at Shafter and Davis, CA, during 1977

	Viable propagules (P) per gram or 100 g of soil at the indicated depths							Colonized carrots (%)		
	Verticillium dahliae (P/g)			*Pythium* spp. (P/g)			*Rhizoctonia solani* (P/100 g)	*Thielaviopsis basicola*		
Location and treatment[a]	0–15 cm	15–30 cm	46 cm[b]	0–15 cm	15–30 cm	46 cm[b]	0–15 cm	15 cm[b]	30 cm[b]	46 cm[b]
Shafter										
Exp. 1 (14 days)										
Nontarped	67.0	10.0	274.0	239.4	51.5	254.5	4.0	83.3	68.3	73.3
Tarped P-100	1.3	1.7	2.7	6.0	8.7	92.9	0.0	3.3	1.7	23.3
Exp. 2 (28 days)										
Nontarped	87.3	49.3	230.7	324.2	139.4	139.9	3.8	93.3	85.0	81.7
Tarped P-25	0.3	0.0	0.0	0.3	0	6.7	0.0	0.0	0.0	0.0
Tarped P-100	0.0	0.3	0.0	1.0	0.3	4.7	0.0	0.0	0.0	0.0
Davis										
Exp. 1 (14 days)										
Nontarped	269.0	84.0	37.0	460.6	54.5	···	···	25.0	15.0	···
PI + P-100	5.0	17.0	2.0	78.0	22.2	···	···	0.0	3.3	···
PI + P-100 + IU	0.7	0.0	0.0	38.0	64.6	···	···	0.0	1.7	···
Exp. 2 (66 days)										
Nontarped	225.0	95.0	32.0	266.7	60.5	···	···	18.3	13.3	···
PI + P-100	0.0	2.0	0.0	54.5	54.5	···	···	0.0	0.0	···
PI + P-100 + IU	0.0	0.0	0.0	14.1	28.3	···	···	0.0	0.0	···

[a]Transparent polyethylene tarps 25-μm (P-25) and 100-μm (P-100) were placed on the soil on June 29, and July 19, 1977, respectively, at Shafter and Davis, CA. PI = a single irrigation 1 wk before application of plastic. IU = a single flood irrigation under the tarps. *T. basicola* was assayed by spreading soil on living carrot tissue.

[b]Naturally infested soil containing the pathogen was buried in nylon mesh bags at designated depths.

showed large daily fluctuations at 5- and 15-cm depths with the maximum temperature usually occurring for approximately 2 hr each day. Below 15 cm, soil temperatures fluctuated less and reached maximum levels after 11 days. During the experiment air temperatures did not exceed 41 C. Air temperature and solar radiation measurements along with additional soil temperature data are available (21).

Experiments at Davis during 1977 showed results similar to those at Shafter (Table 2). Maximum temperatures at the 30-cm depth were reached approximately 12 days after the tarps were placed on the soil. The highest soil temperatures occurred in the tarped areas that were irrigated under the plastic. The temperature differences between treatments were probably due to the increased heat conduction in soil with a higher water content (2). Air temperatures at this site also did not exceed 41 C.

Soil temperatures were also increased at all depths monitored in tarped plots at the Five Points and Mettler experiments during 1978 (Table 2).

Effects on soil populations of plant pathogenic fungi. Fourteen days of soil tarping at Shafter was sufficient to reduce soil populations of the four plant pathogens by 83–100% within the upper 30 cm of the soil (Table 3). Reductions of 63–95% occurred in soil samples buried at 46 cm. After 28 days, pathogen population densities were further reduced and after 58 days the pathogens were all dead.

Results from experiments carried out at Davis during 1977 (Table 3) showed that *V. dahliae* and *T. basicola* population densities were considerably reduced by tarping whereas *Pythium* spp. were not reduced as much. The addition of an irrigation under the plastic generally improved pathogen control.

The survival of *Pythium* spp. may be partially explained by the presence of *Pythium acanthicum* Drechsler, which is a high-temperature species and can grow at temperatures near 40 C (18). This species comprised 30% of the *Pythium* population in nontarped soil collected from a depth of 15–30 cm. After 58 days of tarping with one irrigation, *P. acanthicum* comprised 64% of the surviving population of *Pythium* spp. in soil from 15–30 cm.

In the Five Points and Mettler experiments, inoculum densities of *V. dahliae* were reduced to less than one propagule per gram in tarped soil from 0–30 cm, whereas population densities in nontarped soil decreased slightly (Table 4). *V. dahliae* also showed significant reductions ($P = 0.05$) of 35 and 23%, respectively, at Five Points and Mettler in soil collected from the 75-cm between tarps. This was probably due to a subsurface conduction of heat from tarped to nontarped soil.

Effects on Verticillium wilt and plant yields. Safflower was planted in the plots at Shafter to verify control of *V. dahliae*. Throughout the growing period, healthy plants in nontarped and tarped soil grew normally. Three months after planting, Verticillium wilt incidence was reduced by 93–100% in tarped compared to nontarped soil (Table 1). Safflower yields were also higher by 199–213%. In addition to the control of disease, a visible reduction in weeds occurred.

In the next year these plots were planted with cotton to test the long-term effects of solarization. In mid-September the percentages of cotton plants with foliar symptoms of Verticillium wilt were significantly reduced in soil previously tarped for 28 days or longer when compared with nontarped areas (Table 1). Thus, solarization treatments for 4 wk or more resulted in control of Verticillium wilt in two successive crops. Cotton lint yields, however, were not significantly different in tarped and nontarped plots owing to heavy insect damage and high air temperatures which masked the effects of Verticillium wilt.

Disease incidence of Verticillium wilt in Acala SJ-2 cotton grown in tarped soil at Davis during 1978 was reduced by 89–95% (Table 5). Lint yields, however, were again not significantly different due to high air temperatures that decreased the effects of Verticillium wilt, and a late development of disease, after most plant growth and cotton lint production had occurred.

Sorghum planted at Five Points immediately after tarps were removed, produced 21% more seed in tarped compared to nontarped plots. Acala SJ-2 cotton, planted in previously tarped areas the following season (1979) showed improved growth, a reduction of Verticillium wilt of 63%, and an increased cotton lint yield of 60% (Table 4). It appears that the additional mixing of nontarped with tarped soil due to the crop of sorghum and the remaining inoculum of *V. dahliae* in the 75-cm nontarped strips reduced the effectiveness of the solarization treatment. At Mettler, Acala SJ-2 cotton also showed a decreased incidence of Verticillium wilt (79%) and an increase in cotton lint yields of 13% in tarped compared to nontarped plots (Table 4).

Effects on mycorrhizal colonization of cotton roots. Plants for mycorrhizal assay grown in tarped soil were taller and produced larger root systems than those grown on nontarped soil. Mycorrhizal colonization was evident in almost all roots from nontarped soil regardless of soil depth. Roots from tarped soil at Shafter showed colonization, although to a lesser extent. Reductions in percent colonized root pieces in soil from 0–15, 15–30, and 30–46-cm depths were 98, 42, and 22, respectively. Of all the soil groups tested for mycorrhizae, soil collected from 0–15 cm at the Shafter site was the only group that did not produce abundant mycorrhizal colonization in cotton roots. This soil also experienced the greatest degree of heating of those tested. At Davis, mycorrhizal colonization in tarped soil was not reduced when compared with that in nontarped soil. The mycorrhizal fungus from the Shafter and Davis soils was tentatively identified as *Glomus fasciculatus* (Thaxter) Gerd. and Trappe.

DISCUSSION

Tarping of moist soil with transparent polyethylene plastic during the hot summer months was highly effective in reducing soil population densities of *V. dahliae, Pythium* spp., *R. solani*, and *T. basicola* and in increasing crop yields. Verticillium wilt was

TABLE 4. Effect of soil solarization during 1978 on the survival of *Verticillium dahliae*, control of Verticillium wilt, and cotton lint yields at Five Points and Mettler, CA, in 1979

Location and treatment[y]	Propagules per gram of soil 0–30 cm: September 1978	Propagules per gram of soil 0–30 cm: May 1979	Cotton - 1979: Foliar symptoms (%)	Cotton - 1979: Lint yield (kg/ha)
Five Points (Acala SJ-2)				
Continuous cotton (7 yr)	...	55.3 a	93.3 a	721 a
Nontarped (1 year fallow)	31.3 a	37.7 b	84.0 b	941 b
Soil between tarps[z]	24.0 b	...	...	...
Tarped P-25	0.0 c	3.7 c	31.4 c	1,507 c
Mettler (Acala SJ-5)				
Nontarped	40.3 a	31.0 a	40.0 a	1,289 a
Soil between tarps[z]	26.3 b	...	...	...
Tarped P-25	0.7 c	2.0 b	8.3 b	1,460 b

[y] Clear 25-μm polyethylene tarps (P-25) were placed on the soil at Five Points on 15 June and removed 13 July 1978. At Mettler tarps were applied 10 August and removed 11 September 1978. In 1979, Acala SJ-2 cotton was planted at Five Points and Acala SJ-5 at Mettler. For each location, values within columns followed by the same letter are not significantly different (Duncan's multiple range test, $P = 0.05$).

[z] Nontarped soil was collected from the center of the 75-cm strip between tarps.

significantly controlled and in some experiments wilt control and reduction in pathogen population extended into the second year after tarping. Thin polyethylene plastic (25 μm) was more efficient for soil heating than a thicker plastic (100 μm) and it was also less expensive.

Maintenance of high soil moisture is necessary for increasing soil conduction of heat and for increasing the sensitivity of organisms to high temperatures. Soil moisture can be provided by drip irrigation (16), shallow furrows, or a preirrigation as shown in this study and others (12,15). A comparison between tarping preirrigated soil vs soil tarped and irrigated under the plastic, showed higher soil temperatures and a more rapid decline in pathogen populations with the latter treatment; however, eradication of all pathogens tested eventually occurred in both treatments. The effectiveness of tarping a preirrigated soil depends on the soil type, moisture content, and the time period between the preirrigation and placement of the tarps. Sandy soils in particular, might work well with preirrigation because tarps could be applied by machine after the irrigation, thus reducing the loss of water.

Temperatures in tarped soils reached levels reported lethal to many soilborne fungi (3). *Rhizoctonia solani* is injured by temperatures of 45 C or within 5 min at 50 C (26). Nelson and Wilhem (20) reported that 40 min at 47 C would kill moist microsclerotia of *Verticillium albo-altrum* (= *V. dahliae*). Aloe plants infested with *P. ultimum* were free of root rot when planted after a treatment at 46 C for 20 min, and chlamydospores of *T. basicola* were no longer viable when held at 40 C for 115 hr (4,13). Maximum daily soil temperatures at depths of 5- and 15-cm usually lasted for several hours and were greater than or close to the above-thermal death temperatures. Control of *V. dahliae, Pythium* spp., and *T. basicola* extended well beyond 15-cm into soils heated to maximum temperatures near 36–38 C. The absence of viable propagules of the above pathogens in soils heated at lower temperatures suggests that a time-temperature (dosage) relationship exists for the thermal killing of soilborne fungi and/or that biological control mechanisms occur in solarized soils as shown with *Fusarium* sp. and *R. solani* (10,16).

Microsclerotia of *V. dahliae* are multicellular and can produce as many as 30 germ tubes (8). Presumably all cells must die to inactivate a propagule. However, the root-infecting ability of a heat-weakened propagule is now known. Garber (11) has shown that several hyphae of *V. dahliae* were more successful in penetrating cortical tissues of cotton roots than were single hyphae. Soil heating at sublethal temperatures in the present studies and in others (12,16) impaired the ability of *V. dahliae* to penetrate the plant and cause plant disease. In addition, it is possible that sublethal temperatures reduced the infectivity of individual microsclerotia by changing the population of surrounding soil organisms.

V. dahliae was eliminated or present at less than three propagules per gram of soil in tarped soil between 0–46 cm. The reduction of viable propagules at these depths indicates that control probably extended well beyond 46 cm. Consequently, disease incidence was reduced in all experiments. However, in one case where cotton was a second crop after tarping (Five Points, Table 4), the incidence of Verticillium wilt was greater than expected, apparently due to tarped soil mixing with the adjacent nontarped soil. The use of continuous tarps (no nontarped strips of soil between tarped areas) provides a solution to this problem and will likely increase the long-term effectiveness of soil solarization. Continuous tarping for 4–8 wk can be achieved by gluing the plastic with long-term heat-resistant glue (*unpublished*) or by heat fusion (J. Katan, *personal communication*).

TABLE 5. Effect of soil solarization for 58 days in 1977 on control of Verticillium wilt and cotton lint yields during 1978 at Davis, CA

Treatment[y]	Disease (% foliar symptoms) (21 Sept 1978)	Cotton lint yields (kg/ha)
Nontarped	66 a	550 a
Preirrigated and tarped P-100	3 b	691 a
Preirrigated, tarped (P-100), and IU[z]	7 b	663 a

[y]Tarps P-100 (clear 100-μm polyethylene plastic) were placed on the soil 19 July 1977. Acala SJ-2 cotton was planted in 1978. Values within columns followed by the same letter are not significantly different (Duncan's multiple range test, $P = 0.01$).

[z]IU = A single flood irrigation under the tarps.

Mycorrhizal fungi were present in tarped soils and were able to colonize cotton plant roots. Their survival is essential because root infections with these beneficial fungi can increase cotton plant growth, especially in soils of low fertility (14,25). The thermal death point of *G. fasciculatus* is reported to be 10 min at 51.5 C (17) whereas many plant pathogenic fungi are killed at lower temperatures (1,27). This higher thermal tolerance of mycorrhizal fungi increases the potential usefulness of soil solarization for disease control as compared with fumigation, which might be harmful to these fungi.

Soil solarization provides an effective method for controlling soilborne diseases of cotton, which is simple, nonhazardous, and does not involve toxic materials.

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