Adaptation of Soil Solarization to the Integrated Management of Soilborne Pests of Tomato Under Humid Conditions

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ABSTRACT

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Soil solarization was shown to be cost effective, compatible with other pest management tactics, readily integrated into standard production systems, and a valid alternative to preplant fumigation with methyl bromide under the tested conditions. Solarization using clear, photosensitive, or gas-impermeable plastic was evaluated in combination with metham sodium, 1,3-dichloropropene + chloropicrin, methyl bromide + chloropicrin, pebulate, or cabbage residue. Strip solarization, applied to 20-cm-high, 0.9-m-wide beds, was conducted to achieve compatibility with standard production practices and resulted in soil temperatures 2 to 4°C above those temperatures resulting when using conventional flatbed solarization. Soil temperatures were 1 to 2°C higher at the edges of the raised beds, eliminating any border effects associated with solarization. Following a 40- to 55-day solarization period, the plastic was painted

white and used as a production mulch for a subsequent tomato crop. The incidence of Southern blight and the density of *Paratrachodorus minor* and *Criconebella* spp. were lower ($P < 0.05$) in solarized plots. No differences ($P < 0.05$) in the incidence of Fusarium wilt and the density of nutsedge and *Helicotylenchus* spp. were observed between plots receiving solarization and plots fumigated with a mixture of methyl bromide + chloropicrin. The severity of root galling was lower ($P < 0.05$) when soil solarization was combined with 1,3-dichloropropene + chloropicrin (16.2 + 3.4 g/m²) and a gas-impermeable film. The incidence of bacterial wilt was not affected by soil treatments. Marketable yields in plots using various combinations of soil solarization and other tactics were similar ($P < 0.05$) to yields obtained in plots fumigated with methyl bromide + chloropicrin. The results were validated in several large scale field experiments conducted by commercial growers.

Additional keywords: *Cyperus esculentus*, *C. rotundus*, *Fusarium oxysporum* f. sp. *lycopersici*, *Lycopersicon esculentum*, *Meloidogyne* spp., *Pseudomonas solanacearum*, *Rotylenchulus reniformis*, *Sclerotium rolfsii*.

In Florida and other states, field production of fresh market solanaceous crops is based upon high input, intensively managed production systems requiring the use of broad spectrum fumigants to provide economic control of soilborne pests (5). Since the 1970s, methyl bromide has been used almost exclusively, because of its consistent and effective control of soilborne pests under a range of soil moisture and temperature regimes, relatively low cost, and ease of handling (4,54,56). It has been estimated that a ban on the use of methyl bromide would cost producers and consumers in the United States over \$1 billion annually (2) and would reduce production of tomato, pepper, and eggplant in Florida by 69, 63, and 100%, respectively (46). Concerns about the contribution of methyl bromide to the stratospheric depletion of ozone have led to a ban on its production and importation in the United States beginning January 2001 (10,13).

While several broad spectrum fumigants have been identified as alternatives to methyl bromide (11,21,35,38), use of a single tactic to control soilborne pests still leaves producers vulnerable to future regulatory and marketing policies. For example, half of the soil fumigants used in Florida before 1978 are no longer available, and the remainder have environmental or toxicity problems (4).

Integrated pest management (IPM), which consists of the coordinated use of multiple tactics to maintain pest damage below an economic threshold, offers several advantages over a single tactic approach. Selection of pest management tactics that address the

specific needs and constraints of individual cropping systems eliminates unnecessary pesticide applications and optimizes the performance of existing tactics. IPM fosters the development of selective, biologically based tactics, because the emphasis is on the control of identified pest complexes, not perceived pest threats.

Historically, IPM has not been utilized to control soilborne pests during field production of fresh market solanaceous crops. Preharvest production costs often exceed \$15,000 per hectare (45), leading producers to take measures that reduce the perceived risk of economic loss from soilborne pests. Assessment of soilborne pest complexes in the field is not routinely practiced, creating uncertainty in the selection of tactics. IPM programs are knowledge intensive; they require additional expertise and supplemental management decisions. The development of cultural pest management tactics that are easy to employ, cost effective, and can enhance the efficacy of chemical, cultural, and biological treatments has been limited (31).

Soil solarization is a pest management tactic that has potential application to IPM systems. It is compatible with and often enhances the performance of various chemical, biological, and cultural treatments (14,16,17,34,41-44,53). Soil solarization has been evaluated in several geographic regions where high value crops are cultivated (6,20,25,33,37,39). Its general contribution to IPM systems has been discussed, but it has not been examined within the constraints of specific crop production systems (27,49).

The objective of this study was to evaluate soil solarization as a component in an IPM program for soilborne pests of tomato. Soil solarization was examined for its adaptability to the production system used for this and other similar crops cultivated in humid

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regions, compatibility with other pest management tactics, and effect on soilborne pests and marketable yield.

MATERIALS AND METHODS

Characterization of the cropping system. Fall production of fresh market tomato (*Lycopersicon esculentum* Mill.) in north Florida and south Georgia was used as the model cropping system. Tomatoes are produced on 20-cm-high raised beds covered by white or white on black, low density polyethylene (LDPE) plastic mulch. Beds are prepared and fumigated in June. Tomatoes were transplanted in July and harvested in October. Key soilborne diseases are Fusarium wilt, caused by *Fusarium oxysporum* Schlechtend.:Fr. f. sp. *lycopersici* (Sacc.) W.C. Snyder & H.N. Hans. (races 1, 2, and 3); bacterial wilt, caused by *Ralstonia solanacearum*; and Southern blight, caused by *Sclerotium rolfsii* Sacc. Key weed pests are yellow nutsedge (*Cyperus esculentus* L.) and purple nutsedge (*C. rotundus* L.). Important phytoparasitic nematodes include the root-knot nematode species *Meloidogyne incognita* (Kofoed & White) Chitwood and *M. javanica* (Treub) Chitwood, reniform nematode *Rotylenchulus reniformis* Linford & Oliveira, and stubby-root nematode *Paratrichodorus minor* (Colbran) Siddiqi.

In 1994, field experiments were conducted on tomato production farms located in Decatur County, GA (Georgia-94), and Gadsden County, FL (Florida-94). In 1995, an experiment was conducted at the North Florida Research and Education Center (Florida-95), Gadsden County. In 1995, large scale field validation studies were implemented in three commercial tomato production fields (validation sites I, II, and III). Soil characteristics are presented in Table 1. All locations had been cropped in tomato for five or more consecutive years except the Florida-95 site, which had been left as weed fallow following previous crops of peanut and tobacco.

Georgia-94 and Florida-94 experiments. Eighteen treatments were arranged in a randomized complete block with four replications per treatment. An incomplete factorial design was used in which 16 treatments consisted of all possible combinations of four soil treatments applied under four types of plastic film. Soil treatments were a mixture of methyl bromide + chloropicrin (13.1 + 6.5 g/m²); metham sodium (5.8 g/m²); and cabbage residue (*Brassica oleracea* cv. Constanza) that were dried, shredded, and incorporated into the soil by disking at a rate of 8.0 kg/m²; and an untreated control. Plastic films included a 30-μm-thick, coextruded, white on black LDPE (Edison Plastics Co., Lee Hall, VA); a 30-μm-thick, clear LDPE used for solarization (Polydak film; Polyon Barkai Ltd., Kibbutz, Barkai, Israel); a 25-μm-thick, photoselective LDPE used for solarization (IRT film; AEP Industries, Hackensack, NJ); and a 30-μm-thick, clear, gas-impermeable film used for solarization (Bromotec film; Lawson Mardon Packaging, Workington, Cumbria, United Kingdom). Two additional treatments consisting of metham sodium (11.6 g/m²) and methyl bromide + chloropicrin (26.1 + 13.0 g/m²) were applied under white on black LDPE.

Each replicate plot was 20 m in length and consisted of a single raised bed 20 cm high and 0.9 m wide. Row orientation was north/south. Beds were spaced 1.8 m apart. Fertilizer was incorporated into the beds at 212 kg of N, 65 kg of P, and 212 kg of K per hectare, and drip irrigation tubing was placed 5 cm beneath the soil, 25 cm from the edge of the bed.

Cabbage was grown and harvested in the plots, and the residue incorporated on 23 and 24 May. Beds were prepared and fumigants applied on 3 and 15 June at the Georgia-94 and Florida-94 sites, respectively. The solarization period was terminated by painting the films with a white, latex-based paint (Kool Grow, Gainesville, FL) mixed at a 6:1 dilution with water and applied through a CO₂ backpack sprayer. The painted plastic functioned as a horticultural mulch. Tomato seedlings were transplanted into the

plots on 27 July (cv. BHN 189) and 3 August (cv. Solar Set) at the Georgia-94 and Florida-94 sites, respectively.

Precipitation was recorded daily at both sites. Daily ambient temperature readings were obtained from a National Weather Service Reporting Station located in Gadsden County. Hourly soil temperatures were monitored at the Florida-94 site at depths of 10 and 25 cm using thermocouple sensors. Sensors were placed in the center and 10 cm from the edge of the beds. An electronic data logger automatically processed and recorded analog signals from the sensors (OmniData International, Logan, UT). Two tropical storms severely damaged the Florida-94 site, preventing the collection of additional data from that site. Twelve contiguous plants in the center of each replicate plot were harvested from the Georgia-94 site on 7, 18, and 27 October. Fruit were sorted as marketable and unmarketable based upon size and cosmetic appearance.

Florida-95 experiment. Fifteen treatments were arranged in a randomized complete block with four replications per treatment. A factorial design that consisted of five soil treatments × three plastic films was used. Soil treatments were cabbage residue (cv. Constanza applied at 6.8 kg/m²), pebulate (an herbicide applied at 0.1 g/m²), a mixture of 1,3-dichloropropene + chloropicrin (16.2 + 3.4 g/m²), a mixture of methyl bromide + chloropicrin (13.1 + 6.5 g/m²), and an untreated control. Plastic films were the same as in 1994 except that the photoselective film was omitted.

Plot dimensions and row orientation were the same as in 1994. Cabbage was grown in another location, harvested, and incorporated into plots on 19 May using the same procedures as in 1994. Pebulate was applied and immediately disked into the soil on 25 May. The remaining soil treatments were applied on 26 May. Fertilizer rates were 196 kg of N, 26 kg of P, and 163 kg of K per hectare. The solarization period was terminated when the plastic was painted. Tomatoes (cv. Solar Set) were transplanted on 31 July. Yield data was collected from twelve contiguous plants in the center of each plot on 11, 18, and 26 October.

Daily rainfall and ambient temperature data were recorded. Hourly temperature changes in bare and solarized soil were monitored in beds located in another location approximately 0.5 km from the site. Temperatures were recorded at the soil surface and at depths of 5, 10, 15, 20, and 25 cm using thermocouple sensors connected to an electronic data logger (Campbell Scientific Inc., Logan, UT).

Validation site I. Five treatments were arranged in a randomized complete block with four replications per treatment. Treatments were soil solarization, soil solarization combined with 1,3-dichloropropene + chloropicrin (16.2 + 3.4 g/m²), soil solarization combined with methyl bromide (22.4 g/m²), 1,3-dichloropropene + chloropicrin (32.4 + 6.9 g/m²) applied under white plastic, and methyl bromide (45.0 g/m²) applied under white plastic. Soil solarization treatments were performed using clear, 25-μm-thick LDPE plastic (Polydak film). Each replicate plot consisted of three rows 182 m in length. Row-spacing orientation, bed dimensions, and plant spacings were the same as in previous experiments.

TABLE 1. Characteristics of field soils at the time of solarization and soil treatments

Site	pH	Soil water content (%) ^y	Organic matter (%)	Percent sand-silt-clay (%)	Soil class
Georgia-94	6.6	9.9	1.1	84.0 - 6.0 - 10.0	Kandiudult ^z
Florida-94	5.1	6.1	0.5	88.5 - 4.5 - 7.0	Kandiudult
Validation site I	6.3	9.8	0.4	86.0 - 5.5 - 8.5	Kandiudult
Florida-95	4.7	7.7	1.5	88.5 - 4.0 - 7.5	Kandiudult
Validation site II	6.2	10.3	0.8	87.0 - 6.5 - 6.5	Kandiudult
Validation site III	6.1	9.1	1.0	80.5 - 9.5 - 10.0	Kandiudult

^y Water content expressed as a percentage of the mass of dry soil (gravimetric method).

^z Ultisol with profiles similar to paleudults, but containing higher amounts of kaolinitic clay.

Treatments were applied on 9 June. The solarization period was terminated by painting the plastic, and tomatoes (cv. BHN 189) were transplanted on 19 July. Yield data were obtained by harvesting 12 contiguous plants from the middle row of each replicate plot on 28 September; 10, 19, and 25 October; and 1 November. Daily precipitation and ambient temperature data were obtained from a National Weather Service Reporting Station located 9 km from the study site.

Validation sites II and III. Unreplicated field plots were established on two additional commercial tomato production farms in 1995. Row orientation was north/south in site II and east/west in site III. Soil solarization was performed on 12 rows 210 m in length (0.48 ha) in site II using 30- μ m-thick LDPE (Polydak film) and on seven rows 324 m in length (0.42 ha) in site III using 25- μ m-thick LDPE (Polydak film). Rows adjacent to the solarization

TABLE 2. Environmental conditions during solarization periods

Site	Total precipitation (cm)	Number of days		Maximum ambient temperature $\geq 35^{\circ}\text{C}$
		Solarization period	Precipitation occurred	
Georgia-94	46.0	49	30	0
Florida-94	38.4	48	31	0
Florida-95	30.1	55	17	6
Validation site I	17.4	40	12	6
Validation site II	NA ^z	40	NA	6
Validation site III	NA	36	NA	5

^z Not available.

Fig. 1. Hourly fluctuations in soil temperatures over a 3-day period at the Florida-95 site. **A**, Comparison among temperatures at 10 and 25 cm depths in the center and 10 cm from the edge of a 0.9-m-wide, 20-cm-high bed covered by clear, low density polyethylene plastic. **B**, Temperature profile at various depths within the center of the raised bed.

treatment were fumigated with methyl bromide (45 g/m²) and covered with a white over black, coextruded LDPE (Edison Plastics Co.). Soil disinfestation treatments were applied on 9 June in site II and 13 June in site III. The solarization period was terminated by painting the plastic white. Tomato seedlings (cv. Solar Set) were transplanted into all treatments. Yield data were obtained by harvesting 12 contiguous plants from four different locations each within both the solarized and methyl bromide-treated areas.

Assessment of pest control. In locations where *Cyperus* spp. were present, assessment of control was made by counting the number of plants emerging through the plastic over a 12-m-long section and computed as an average per 0.27 m² of bed. Ratings were taken at the end of the solarization period, prior to transplanting. In locations where symptoms of soilborne diseases were present, disease incidence was assessed by counting the number of plants with symptoms in each replicate plot and dividing by the total number of plants present in each replicate plot. Soil samples for nematode analysis were collected by removing and combining soil cores 2.5 cm wide and 20 cm deep from the root zone of each of six plants per plot. Nematodes were extracted from 100-cm³ soil subsamples with a modified sieving and centrifugation procedure (28), and then identified and counted. In locations where root galling from *Meloidogyne* spp. was present, root systems from five plants in each replicate plot were removed and rated for root galling on a 0 to 5 scale (52) in which 0 = no galls per root system, 1 = one to two galls per root system, 2 = three to 10 galls per root system, 3 = 11 to 30 galls per root system, 4 = 31 to 100 galls per root system, and 5 = more than 100 galls per root system.

Evaluation of soil heating under raised beds. Soil temperatures under a flat surface and 20-cm raised beds were recorded to obtain information on the efficiency of strip solarization performed on raised beds. The comparison was made between 30 August and 23 September 1995 in a location near the Florida-95

Fig. 2. Hourly fluctuations in soil temperatures at 5 and 15 cm depths over a 3-day period under a 0.9-m-wide sheet of clear, low density polyethylene plastic stretched over a flat surface or a 20-cm-high bed. **A**, Soil temperatures at 10 cm from the east edge of the plastic strip. **B**, Soil temperatures from the center of the plastic strip.

site. A 0.9×10.0 -m sheet of clear, 25- μ m-thick, LDPE (Polydak film) was stretched over a flat soil surface and a over raised bed 20 cm high and 0.9 m wide. Soil moisture at initiation of the comparison was 15.6%. Daily precipitation and ambient temperature data were recorded at the site. Hourly changes in soil temperatures were monitored in the raised and flat beds at 5 and 15 cm depths using thermocouple sensors connected to an electronic data logger (Campbell Scientific Inc.). Row orientation was north/south. Soil temperatures were monitored 10 cm from the edge on the west and east side of the bed and in the center of the bed.

Statistical analysis. Nematode counts were log-transformed ($\log_{10} [x + 1]$) and disease incidence data were transformed using the arc sine transformation ($\sin^{-1}$ square root x) prior to analysis. Analysis of variance was performed with PROC GLM of SAS (release 6.04 for personal computers; SAS Institute, Cary, NC) for all data except nematode density counts, which were analyzed using MSTAT (Michigan State University, East Lansing). The Waller-Duncan k -ratio t test was used to compare all treatment means except for nematode density counts, which were compared using Duncan's multiple range test.

RESULTS

Site conditions. Soil water content, expressed as a percentage of the mass of dry soil, ranged from 6.1 to 10.3% at the onset of

solarization and fumigation treatments (Table 1). The solarization periods ranged from 36 to 55 days (Table 2). In 1994, precipitation was recorded on at least 30 different days in the solarization period at both sites (Table 2). In 1995, precipitation occurred on 12 and 17 different days in the solarization period at the Florida-95 site and validation site I, respectively.

Soil temperatures. At the Florida-94 site, the maximum temperature at a 10 cm depth was 41.5°C under bare soil and 41.8, 45.7, and 49.2°C under white, photoselective, and clear plastic, respectively. At a 25 cm depth, the maximum soil temperature was 34.6°C under bare soil and 34.7, 37.3, and 38.0°C under white, photoselective, and clear plastic, respectively. Addition of cabbage residue did not increase soil temperature.

At the Florida-95 site, the maximum soil temperature at a 10 cm depth was 42.4°C under bare soil and 48.7°C under clear LDPE. At a 25 cm depth, the maximum soil temperature was 35.1°C under bare soil and 40.3°C under clear LDPE. Soil temperatures near the edge of the plastic were 1 to 2°C higher than in the center (Fig. 1A). Under clear LDPE, the maximum soil temperature declined rapidly from 61.3°C at the surface to 53.2°C at a 5 cm depth (Fig. 1B). At depths of 5 and 15 cm, higher soil temperatures were achieved when solarization was performed on a raised bed as opposed to on a flat surface (Fig. 2A and B). The differences were more pronounced at the edges of the bed than in the center. On a raised bed, temperatures at the edges often exceeded those in the center (Fig. 2).

TABLE 3. Effects^w of soil treatments and solarization with various plastic films on soilborne pests and yield of fresh market tomato at the Georgia-94 site

Soil treatment	Rate per m ²	Plastic film ^{x,y}				Mean ^y
		Clear, GI	White	Clear	IRT	
<i>Fusarium wilt</i>						
None	...	0.0 d	7.2 a	0.0 d	1.0 cd	2.0
Cabbage	8.0 kg	0.9 cd	5.6 ab	0.0 d	2.0 cd	2.1
Metham-Na	5.8 g	0.0 d	3.8 bc	0.9 cd	0.9 cd	1.4
MBC ^z	13.1 + 6.5 g	0.0 d	0.0 d	0.0 d	0.0 d	0.0
Mean		0.2	4.2	0.2	1.0	
<i>Bacterial wilt</i>						
None	...	4.4	15.6	20.7	4.9	11.4
Cabbage	8.0 kg	10.0	20.5	2.9	23.6	14.2
Metham-Na	5.8 g	9.2	18.5	33.4	19.4	20.1
MBC	13.1 + 6.5 g	19.2	5.0	9.6	10.1	11.0
Mean		10.7	14.9	16.6	14.5	
<i>Paratrichodorus minor</i>						
None	...	13.8	9.5	18.5	21.2	15.8 C
Cabbage	8.0 kg	21.8	29.0	17.8	16.8	21.3 BC
Metham-Na	5.8 g	14.5	50.0	23.8	37.8	31.5 AB
MBC	13.1 + 6.5 g	21.8	62.2	38.8	21.0	35.9 A
Mean		17.9 B	37.7 A	24.7 B	24.2 B	
<i>Cyperus</i> species						
None	...	0.1 b	12.0 a	0.1 b	<0.1 b	3.1
Cabbage	8.0 kg	0.2 b	3.1 b	<0.1 b	0.5 b	1.0
Metham-Na	5.8 g	0.1 b	3.0 b	<0.1 b	0.2 b	0.8
MBC	13.1 + 6.5 g	<0.1 b	0.5 b	<0.1 b	0.2 b	0.2
Mean		0.1	4.6	0.1	0.2	
Marketable yield						
None	...	45.4 a	23.2 c	48.5 a	42.6 ab	39.9
Cabbage	8.0 kg	51.7 a	28.7 c	50.9 a	32.2 bc	40.9
Metham-Na	5.8 g	53.7 a	46.2 a	42.0 ab	45.7 a	46.9
MBC	13.1 + 6.5 g	46.7 a	49.3 a	47.0 a	46.0 a	47.2
Mean		49.4	36.9	47.1	41.6	

^w Effects are stated for *Fusarium wilt* and bacterial wilt as the percent of disease incidence, for *Paratrichodorus minor* as the density of nematodes per 100 cm³ of soil (samples collected 62 days after transplanting), for *Cyperus* species as the number of plants per 0.27-m² area that emerged through the plastic at the termination of the solarization period, and for marketable yield as metric tons per hectare.

^x Clear, GI = clear, gas-impermeable solarization film; white = white on black, coextruded, low density polyethylene (LDPE); clear = clear LDPE solarization film; and IRT = a photoselective solarization film with transmission values of 15% for photosynthetically active radiation and 23% for total radiation.

^y Main effect means for plastic film or soil treatment followed by the same letter (A, B, or C) do not differ according to the Waller-Duncan k -ratio t test ($P \leq 0.05$). Means for the interaction of soil treatment and plastic film followed by the same letter (a, b, c, or d) do not differ according to the Waller-Duncan k -ratio t test ($P \leq 0.05$).

^z A mixture of methyl bromide + chloropicrin.

Soilborne diseases. There was a significant interaction between the effects of soil treatments and plastic film on the incidence of Fusarium wilt at the Georgia-94 site (Table 3). Plots receiving soil solarization or methyl bromide had significantly lower levels of disease than plots receiving metham sodium. Doubling the rate of metham sodium did not result in lower levels of disease (Table 4). Fusarium wilt was not detected at the other sites.

At the Georgia-94 site, neither soil treatment nor plastic had a significant effect on the incidence of bacterial wilt (Table 3). Doubling the rate of methyl bromide + chloropicrin resulted in significantly higher levels of bacterial wilt (Table 4). Doubling the rate of metham sodium did not affect the level of disease. Bacterial wilt was observed in validation sites I and II, but the incidence was below 1%.

Soil treatment and plastic film had a significant effect on the incidence of Southern blight at the Florida-95 site (Table 5). Disease levels were higher in the plots receiving only cabbage amendment and were lower in plots receiving soil solarization. In validation site II, the incidence of Southern blight was <0.1% in the solarized area and 3.7% in the areas treated with methyl bromide (Table 6).

Yellow and purple nutsedge. A significant interaction between soil treatment and plastic was observed at the Georgia-94 and Florida-95 sites. At the Georgia-94 site, nutsedge pressure was less severe, and both soil solarization and methyl bromide + chloropicrin provided significant control of mixed populations of yellow and purple nutsedge (Table 3). Doubling the dosage of methyl bromide + chloropicrin or metham sodium did not increase the level of control (Table 4). In the Florida-95 site, nutsedge pressure was more intense, and only treatments with solarization provided significant levels of control (Table 5).

Phytoparasitic nematodes. Soil treatment and plastic had a significant effect on the density of *Paratrichodorus minor* at the

Georgia-94 site (Table 3). Significantly lower densities of *Paratrichodorus minor* were observed in the plots receiving solarization. Doubling the dosage of fumigants did not affect the density of *Paratrichodorus minor* (Table 4). In the Florida-95 site, soil treatment and plastic also had a significant effect on the density of *Paratrichodorus minor* (Table 7).

The density of *Paratrichodorus minor* was lower in areas receiving soil solarization in validation sites II and III (Table 6), but not in validation site I (Table 8). In all five sites examined, application of methyl bromide + chloropicrin failed to reduce the density of *Paratrichodorus minor* (Tables 3, 4, 6, 7, and 8).

A significant interaction between soil treatment and plastic was observed for the severity of root galling by *Meloidogyne* spp. at the Florida-95 site (Table 5). Treatments receiving methyl bromide + chloropicrin or the combination of soil solarization, 1,3-dichloropropene + chloropicrin, and a gas-impermeable plastic had significantly lower levels of root galling. Soil treatment had a significant effect on the density of *Meloidogyne* spp. at the Florida-95 site (Table 7). At validation site I, treatments did not significantly impact the density of *Meloidogyne* spp. (Table 8).

At the Florida-95 site, the density of *R. reniformis* was significantly lower in plots receiving methyl bromide + chloropicrin or 1,3-dichloropropene + chloropicrin (Table 7). The density of *R. reniformis* in validation site III was lower in plots treated with methyl bromide (Table 6).

Significant reductions in *Cricanemella* and *Helicotylenchus* spp. were achieved using soil solarization, methyl bromide + chloropicrin, and 1,3-dichloropropene + chloropicrin (Table 7).

Marketable yield. A significant interaction between soil treatment and plastic was observed at the Georgia-94 and Florida-95 sites. No significant difference in yield was observed between plots receiving methyl bromide + chloropicrin or soil solarization at the Georgia-94 site except for plots that received cabbage + solarization using the photosensitive plastic, which was significantly lower (Table 3). Doubling the rate of metham sodium did not affect yield. Doubling the rate of methyl bromide + chloropicrin resulted in significantly lower yields, because of the increased incidence of bacterial wilt. At the Florida-95 site, the interactions between plastic and soil treatment were complex. Yields in plots receiving solarization, solarization and methyl bromide + chloropicrin, or solarization and 1,3-dichloropropene + chloropicrin were significantly higher than yields in plots receiving soil treatments applied under white plastic (Table 5). At validation site I, yields in plots treated with a high rate of 1,3-dichloropropene + chloropicrin were significantly higher than yields in plots receiving only solarization (Table 8). At validation sites II and III, yields in areas treated with soil solarization were similar to yields in areas treated with methyl bromide (Table 6).

DISCUSSION

Soil solarization has been traditionally considered a soil disinfection technique suitable for arid climates. In recent years, reports of its application potential in humid regions characterized by abundant rainfall and cloud cover have been published (8,9,19,20,30,33,34,37,39,43,44). In this study, precipitation occurred on 30 to 64% of the solarization days, yet marketable yields of fresh market tomato in plots receiving soil solarization were similar or greater than yields in plots receiving methyl bromide. In the large scale field plots, yields in areas receiving solarization were similar to yields in methyl bromide-treated areas, validating the application potential of soil solarization.

Although the yield potential of treatments receiving soil solarization was demonstrated, it should be noted that not all soilborne pests were suppressed when soil solarization was employed alone. Soil solarization failed to reduce densities of *R. reniformis* and *Meloidogyne* spp. and the severity of root galling in the Florida-95 experiment and in validation site I. In the Florida-95 site, a mix-

TABLE 4. Contrast among treatments at the Georgia-94 site under white plastic receiving reduced and full rates of methyl bromide + chloropicrin (MBC) or metham sodium (Metham-Na)

Treatment	Rate per m ²	Control assessment ^y	<i>PR</i> > <i>F</i> ^z
Marketable yield			
Metham-Na	5.8 g	46.3	0.76
Metham-Na	11.6 g	41.9	
MBC	13.1 + 6.5 g	49.3	
MBC	26.2 + 13.0 g	39.8	
<i>Cyperus</i> species			
Metham-Na	5.8 g	3.0	0.99
Metham-Na	11.6 g	7.7	
MBC	13.1 + 6.5 g	0.5	0.91
MBC	26.2 + 13.0 g	0.3	
Bacterial wilt			
Metham-Na	5.8 g	10.0	0.66
Metham-Na	11.6 g	18.5	
MBC	13.1 + 6.5 g	5.0	0.05
MBC	26.2 + 13.0 g	13.5	
Fusarium wilt			
Metham-Na	5.8 g	3.8	1.00
Metham-Na	11.6 g	5.7	
MBC	13.1 + 6.5 g	0.0	0.98
MBC	26.2 + 13.0 g	1.0	
<i>Paratrichodorus minor</i>			
Metham-Na	5.8 g	50.0	0.70
Metham-Na	11.6 g	58.0	
MBC	13.1 + 6.5 g	62.2	0.20
MBC	26.2 + 13.0	38.2	

^y Assessment for marketable yield is the yield in metric tons per hectare, for *Cyperus* species is the number of plants emerging per 0.27-m² area, for bacterial wilt and Fusarium wilt is the percent of disease incidence, and for *Paratrichodorus minor* is the number of nematodes per 100 cm³ of soil.

^z The significance probability value associated with the F value.

ture of *M. incognita* and *M. javanica* was identified. Significant reductions in *M. javanica* and *M. incognita* by soil solarization have been reported (1,39,40,48,51). Reductions in *R. reniformis* by soil solarization also have been reported (1,6,9,26). The lack of control of *Meloidogyne* spp. and *R. reniformis* may be due to nematode recolonization of treated soil. In several studies in which soil so-

larization suppressed initial populations, recolonization was shown to occur (1,6,26,40). At the Florida-95 site, nematode samples were not collected until 80 days after transplanting, allowing sufficient time for recolonization to occur. Strip solarization, in which 50% of the field was untreated, may have further enhanced recolonization. In a previous study performed in the same production

TABLE 5. Effects^u of soil treatments and solarization with various plastic films on soilborne pests and yield of fresh market tomato at the Florida-95 site

Soil treatment	Rate per m ²	Plastic film ^{v,w}			Mean ^w
		Clear, GI	White	Clear	
Southern blight ^x					
None	...	2.0	11.0	4.2	5.8 B
Pebulate	0.1 g	5.6	8.5	4.0	6.1 B
Cabbage	6.8 kg	9.5	19.2	5.5	11.4 A
1,3-DCPC ^y	16.2 + 3.4 g	3.2	4.2	1.8	3.1 B
MBC ^z	13.1 + 6.5 g	3.2	2.0	3.0	2.8 B
Mean		4.8 B	9.0 A	3.7 B	
Root gall ratings					
None	...	3.6 abcd	2.8 def	3.2 bcde	3.2
Pebulate	0.1 g	4.0 abc	4.0 abc	4.5 a	4.2
Cabbage	6.8 kg	3.0 cde	4.5 a	4.3 ab	3.9
1,3-DCPC	16.2 + 3.4 g	0.8 gh	2.4 ef	1.8 fg	1.6
MBC	13.1 + 6.5 g	0.2 h	0.4 h	0.8 gh	0.4
Mean		2.3	2.8	2.9	
<i>Cyperus</i> species					
None	...	0.1 c	33.4 b	0.9 c	11.4
Pebulate	0.1 g	0.0 c	25.2 b	0.6 c	8.6
Cabbage	6.8 kg	0.0 c	56.1 a	0.6 c	18.9
1,3-DCPC	16.2 + 3.4 g	0.0 c	61.6 a	0.5 c	20.7
MBC	13.1 + 6.5 g	0.0 c	48.6 a	0.4 c	16.3
Mean		< 0.1	45.0	0.6	
Marketable yield					
None	...	42.8 ab	17.5 efg	30.3 bcd	30.2
Pebulate	0.1 g	27.0 cde	6.8 g	35.2 bc	23.0
Cabbage	6.8 kg	30.8 bcd	11.2 fg	41.1 ab	27.7
1,3-DCPC	16.2 + 3.4 g	36.0 bc	20.6 def	37.7 abc	31.4
MBC	13.1 + 6.5 g	50.2 a	14.1 fg	41.3 ab	35.2
Mean		37.3	14.1	37.4	

^u Effects are stated for Southern blight as the percent of disease incidence, for root gall rating as an estimate of the number of galls per root system using a scale of 0 to 5 in which 0 = no galls and 5 = >100 galls (52), for *Cyperus* species as the number of plants per 0.27-m² area emerging through the plastic at the termination of the solarization period, and for marketable yield as metric tons per hectare.

^v Clear, GI = clear, gas-impermeable solarization film; white = white on black, coextruded, low density polyethylene; and clear = clear, low density polyethylene solarization film.

^w Main effect means for plastic film or soil treatment (A and B) followed by the same letter do not differ according to the Waller-Duncan *k*-ratio *t* test ($P \leq 0.05$). Means for the interaction of soil treatment and plastic film followed by the same letter (a to h) do not differ according to the Waller-Duncan *k*-ratio *t* test ($P \leq 0.05$).

^x Incidence of Southern blight caused by *Sclerotium rolfsii*.

^y A mixture of 1,3-dichloropropene + chloropicrin.

^z A mixture of methyl bromide + chloropicrin.

TABLE 6. Effect of soil solarization on soilborne pests and marketable yield of tomato in validation sites II and III

Plastic ^r	Soil treatment	Rate ^s	Southern blight ^t	<i>Paratrichodorus minor</i> ^u	<i>Rotylenchulus reniformis</i> ^u	<i>Meloidogyne</i> species ^u	Root gall index ^v	Marketable yield ^w
Validation site II ^x								
Clear	None	...	<0.1%	11.8	...	0.5	0.3	54.4
White	MBC ^y	45 g	3.7%	35.5	...	0.0	0.2	50.9
Validation site III ^z								
Clear	None	...	...	31.8	44.5	...	...	60.6
White	MBC	45 g	...	45.0	0.5	...	...	61.4

^r Clear = clear, low density polyethylene solarization film and white = white on black, coextruded low density polyethylene.

^s Per square meter.

^t Disease incidence.

^u Number of nematodes per 100 cm³ of soil.

^v Estimates of the number of galls per root system using a scale of 0 to 5 in which 0 = no galls and 5 = >100 galls (52).

^w Metric tons per hectare.

^x Solarization performed on 0.48 ha (12 rows, 210 m long).

^y A 98:2 mixture of methyl bromide + chloropicrin.

^z Solarization performed on 0.42 ha (7 rows, 324 m long).

region, broadcast solarization provided season-long reduction in populations of *R. reniformis* (9). Evidence for late-season recolonization is supported by the fact that although high numbers of *R. reniformis*, *Meloidogyne* spp., and severe root galling were found in

the Florida-95 experiment and in validation sites I and II, yield of marketable fruit was not affected. Several studies in which recolonization occurred also showed no effect of the nematode damage on yield (1,26). Strip solarization, as practiced here, was ef-

TABLE 7. Effects of soil treatments and solarization using various plastic films on the density of phytoparasitic nematodes per 100 cm³ of soil at the Florida-95 site^v

Soil treatment	Rate per m²	Plastic film ^w			Mean ^x
		Clear, GI	White	Clear	
<i>Meloidogyne</i> species					
None	...	2,254	315	418	1,096 A
Pebulate	0.1 g	532	566	2,598	1,232 A
Cabbage	6.8 kg	1,219	1,140	978	1,112 A
1,3-DCPC ^y	16.2 + 3.4 g	46	619	635	434 AB
MBC ^z	13.1 + 6.5 g	<1	6	7	4 B
Mean		870	529	927	
<i>Rotylenchulus reniformis</i>					
None	...	126	203	353	228 AB
Pebulate	0.1 g	222	104	353	226 AB
Cabbage	6.8 kg	375	354	416	382 A
1,3-DCPC	16.2 + 3.4 g	54	62	54	57 BC
MBC	13.1 + 6.5 g	4	4	22	10 C
Mean		156	145	239	
<i>Paratrichodorus minor</i>					
None	...	16	15	10	13 A
Pebulate	0.1 g	3	12	3	6 A
Cabbage	6.8 kg	7	20	11	13 A
1,3-DCPC	16.2 + 3.4 g	3	28	18	16 A
MBC	13.1 + 6.5	2	16	20	13 A
Mean		6 B	18 A	12 AB	
<i>Cricanemella</i> species					
None	...	6	64	10	27 AB
Pebulate	0.1 g	18	121	58	66 AB
Cabbage	6.8 kg	34	192	32	86 A
1,3-DCPC	16.2 + 3.4 g	1	22	0	8 B
MBC	13.1 + 6.5 g	0	5	0	2 B
Mean		12 B	81 A	20 B	
<i>Helicotylenchus</i> species					
None	...	2 a	101 a	11 ab	38
Pebulate	0.1 g	9 a	62 a	14 a	28
Cabbage	6.8 kg	3 a	83 a	4 ab	30
1,3-DCPC	16.2 + 3.4 g	0 a	0 b	1 b	<1
MBC	13.1 + 6.5 g	<1 a	0 b	<1 b	<1
Mean		3	49	6	

^v Samples collected 80 days after transplanting.

^w Clear, GI = clear, gas-impermeable solarization film; white = white on black, coextruded, low density polyethylene; and clear = clear, low density polyethylene solarization film.

^x Main effect means for plastic film or soil treatment (A, B, and C) followed by the same letter do not differ ($P \leq 0.05$) according to Duncan's multiple range test. Means for interactions between plastic film and soil treatments followed by the same letter (a and b) do not differ ($P \leq 0.05$) according to Duncan's multiple range test.

^y A mixture of 1,3-dichloropropene + chloropicrin.

^z A mixture of methyl bromide + chloropicrin.

TABLE 8. Effect of soil solarization and chemical fumigants on soilborne pests and marketable yield of tomato at the validation site III

Plastic ^s	Soil treatment	Rate ^t	<i>Paratrichodorus minor</i> ^u	<i>Meloidogyne</i> species ^u	Root gall ratings ^v	Marketable yield ^w
White	MBC ^x	45.0 g	31.0 a ^y	18.0 a	0.0 c	52.0 ab
White	1,3-DCPC ^z	32.4 + 6.9 g	19.5 a	2.5 a	0.2 bc	60.3 a
Clear	MBC	22.4 g	17.2 a	706.5 a	1.0 b	51.6 ab
Clear	1,3-DCPC	16.2 + 3.4 g	24.8 a	151.0 a	0.1 b	45.6 b
Clear	None	...	31.8 a	385.0 a	1.8 a	44.4 b

^s White = white, low density polyethylene and clear = clear, low density polyethylene solarization film.

^t Per square meter.

^u Density of nematodes per 100 cm³ of soil.

^v Estimates of the number of galls per root system using a scale of 0 to 5 in which 0 = no galls and 5 = >100 galls (52).

^w Metric tons per hectare.

^x A 98:2 mixture of methyl bromide + chloropicrin.

^y Means in each column followed by the same letter do not differ ($P \leq 0.05$) according to the Waller-Duncan *k*-ratio *t* test (root gall ratings and marketable yield) or Duncan's multiple range test (*Paratrichodorus minor* and *Meloidogyne* spp.).

^z A mixture of 1,3-dichloropropene + chloropicrin.

fective in reducing populations of *Paratrichodorus minor*, which commonly recolonizes fumigated soil, although trichodorid recolonization tends to occur from residual populations in deeper soil layers (55) rather than from nonfumigated strips.

Soil solarization provided significant reductions in the incidence of Southern blight and Fusarium wilt and was generally as effective as fumigation with methyl bromide + chloropicrin. Reductions in the incidence of diseases caused by *S. rolfii* have been reported in other studies; although, in some instances, the effect varied from year to year (22,43,51). Reductions in the incidence of Fusarium wilt of tomato, cumin, and cotton by soil solarization also have been reported (15,32,36,41). Soil solarization resulted in significant levels of disease suppression even though it failed to significantly reduce populations of *F. oxysporum* f. sp. *lycopersici* in a previous study (8). Suppression of Fusarium wilt in the absence of a direct effect on pathogen survival is considered to be related to the involvement of fluorescent pseudomonads and other microorganisms in solarized soils (15).

The inability of soil solarization to control bacterial wilt agrees with earlier studies (8,9). Previous studies have shown a synergistic interaction between fumigation with methyl bromide + chloropicrin and soil solarization on survival of *Ralstonia solanacearum* and the incidence of bacterial wilt (8,9). This interaction was not observed in this study, perhaps because strip solarization left untreated areas that served as inoculum sources.

The efficacy of some soil disinfestation tactics was enhanced through the combination of soil solarization and improvements in plastic technology. For example, soil solarization and 1,3-dichloropropene + chloropicrin did not significantly reduce the severity of root galling (Table 5) when used alone. When the treatments were applied under a gas-impermeable plastic, the level of root galling was significantly reduced. While not significant at $P < 0.05$, a 10-fold reduction in the density of *Meloidogyne* spp. was also observed using this combination. Stapleton et al. (50) did not observe additional reductions in the density of *M. incognita* when soil solarization was combined with 1,3-dichloropropene. In this study, significant reductions occurred only when the gas-impermeable film was added. Polyethylene is only marginally effective in preventing chemical fumigants, including methyl bromide and 1,3-dichloropropene, from escaping into the atmosphere (12). Estimates of emissions of methyl bromide between 40 and 99% have been reported under LDPE plastic (18,29). The gas-impermeable "Bromotec" plastic (Lawson Mardon Packaging) consists of two layers of LDPE sandwiched around a nylon core. The nylon core gives the film its impermeable properties and has been shown to reduce methyl bromide emissions to levels less than 3% (7).

Soil amended with cabbage residue prior to solarization did not produce any additional benefits in the suppression of soilborne pests. Other studies have observed beneficial effects from combining cabbage residue with soil solarization treatments (16,34). It is possible that the concentration of antifungal volatile compounds evolved from solarized soil amended with cabbage residue was not high enough to provide additional control under the field conditions in this study. Retention of volatiles through the use of a gas-impermeable film did not improve efficacy. In this study, the cabbage residue was scattered onto the plots and then mixed with the soil as the raised beds were prepared. It was not ground into powder and uniformly mixed as was the case in the study by Gamliel and Stapleton (16). Large pieces of undecomposed cabbage may not have been affected by the heat treatment, and, rather than emitting biotoxic volatiles, may have served as a substrate for *S. rolfii*, leading to higher levels of Southern blight in the cabbage-amended plots.

Other studies have investigated soil solarization performed on raised beds (24,25,33,34,44,47). This is the first study in which solarization of raised beds was shown to eliminate the border effect that results from a decrease in soil temperatures at the edge of

the solarized area (23). With a raised bed, the plastic film on the sides of the bed provides additional surface area for solar radiation to penetrate the soil and functions as a barrier to prevent heat escaping from the edges of the treated area.

The soil solarization treatments were fully compatible with the regional fresh market fall tomato production system. The plastic was applied during the routine application window, and growers did not have to modify their application procedures. The cost of the clear LDPE was half of the cost of white on black, coextruded LDPE. The only additional procedure required of the solarization process was painting the plastic white at the end of the solarization period. The cost of paint was \$135 per hectare. Per hectare costs of the standard soil disinfestation procedure, including plastic film and methyl bromide + chloropicrin, is approximately \$1,535. The per hectare cost of the soil solarization treatment, including the paint, is approximately \$548. Thus, soil solarization was more cost effective, resulting in savings approaching \$1,000 per hectare. The solarization film provided an added benefit as it was also used as a production mulch after the solarization treatment was completed. Full integration of soil solarization into standard, raised-bed, plastic mulch production systems has been attempted in only a few instances (24,25,44).

Without any soil disinfestation treatment, marketable yields averaged 20.4 metric tons per hectare, which was a 50% reduction from the Florida state-wide average of 40.1 metric tons per hectare observed between 1991 and 1995 (3). Although less than the 61.4% reduction in production reported by Spreen et al. (46), this study further substantiates the claim that failure to obtain alternatives to methyl bromide for management of soilborne pests will result in major economic hardships for Florida vegetable producers. For example, using a 5-year average market price of \$7.95 per 11.35-kg box, the 50% reduction in marketable yield represents an annual loss of \$281 million from fresh market tomato production in Florida.

In this study, soil solarization was shown to be ideally suited to function as a framework in which to establish an IPM program for soilborne pests. Soil solarization integrated well into the raised-bed, plastic mulch production system, was cost effective, provided significant management of many of the key pests, enhanced the efficacy of other pest management tactics, and permitted reduced dosages of chemical fumigants. The decline in the availability of chemical fumigants coupled with an increase in the availability of biological control agents and new developments in plastic technology will continue to support the utilization of soil solarization in an IPM program for soilborne pests.

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