Effects of Soil Solarization and Fumigation on Survival of Soilborne Pathogens of Tomato in Northern Florida

D. O. CHELLEMI and S. M. OLSON, University of Florida, North Florida Research and Education Center, Route 3, Box 4370, Quincy 32351, and D. J. MITCHELL, University of Florida, Department of Plant Pathology, Gainesville 32611

ABSTRACT

Chellemi, D. O., Olson, S. M., and Mitchell, D. J. 1994. Effects of soil solarization and fumigation on survival of soilborne pathogens of tomato in northern Florida. Plant Dis. 78:1167-1172.

The effects of soil solarization and fumigation, alone or combined, on survival of *Fusarium oxysporum* f. sp. *radicis-lycopersici, F. o. lycopersici, Phytophthora nicotianae* (= *P. parasitica*), and *Pseudomonas solanacearum* were examined in field plots in northern Florida. Soil solarization was performed over a 32- to 49-day period using a photoselective, low-density polyethylene film. Soil was fumigated with a 67:33 mixture of methyl bromide:chloropicrin. Precipitation occurred on 14 and 23 days during solarization periods in 1992 and 1993, respectively. Maximum temperatures recorded at depths of 5, 15, and 25 cm were 43.8, 38.9, and 36.5 C in bare soil and 49.5, 46.0, and 41.5 C in solarized soil. Soil solarization resulted in a significant ($P \leq 0.05$) decrease in the density of *Phytophthora nicotianae* and *P. solanacearum* down to a depth of 25 and 15 cm, respectively. Significant reductions in the density of *F. o. radicis-lycopersici* and *F. o. lycopersici* following soil solarization occurred only in the upper 5 cm of soil. Fumigation significantly reduced populations of *Phytophthora nicotianae, F. o. radicis-lycopersici*, and *F. o. lycopersici* down to a depth of 35 cm. The effect of fumigation on *P. solanacearum* was highly variable. Additional reductions in the density *P. solanacearum* were achieved when solarization was combined with fumigation.

Additional keywords: bacterial wilt, Fusarium crown rot, Fusarium wilt

Soilborne diseases have a major impact on the cultivation of horticultural crops in humid tropical and subtropical regions. In production systems where polyethylene film is used as a mulch, preplant application of chemical fumigants is the principal method employed for control of soilborne pests. In Florida, for example, 4.9 million kg of methyl bromide was applied to 20,000 ha of tomato (*Lycopersicon esculentum* Mill.) during 1990 to control soilborne pests (1,2). Increased social and legislative pressure to restrict the use of chemical fumigants has created the impetus to evaluate alternative approaches for management of soilborne diseases.

Soil solarization has been used in 38 countries to suppress soilborne pests (16). The majority of the successful applications originate from climates characterized as hot, dry, and cloudless with little rain. Soil solarization has shown potential for suppression of soilborne pests in climates with frequent precipitation. In the southeastern United States, populations of *Rotylenchulus reniformis* Linford & Oliveira, *Paratrichodorus minor* (Colbran) Siddiqi, and *Cyperus* spp., levels of root galling of tomato by *Meloidogyne* spp., and incidence of southern blight of tomato, caused by *Sclerotium rolfsii* Sacc., have been reduced (24,28,30). In tropical and subtropical climates, frequent rain events and extended periods of cloud cover can reduce soil temperatures to levels that permit weed seed to germinate and weeds to penetrate or lift up the solarization film, reducing its heat-retention capabilities. There are no reports on the use of photoselective polyethylene film to restrict the growth of weeds during solarization treatments.

The objective of this study was to quantify the effects of soil solarization and fumigation in a subtropical climate (northern Florida) characterized by extended periods of rainfall and frequent cloud cover. A photoselective polyethylene film was used in solarization treatments to suppress weed growth during periods of extended cloud cover.

MATERIALS AND METHODS

Field locations. The research was conducted at one site (CAR) in 1992 and two sites (JAS and QCY) in 1993. Sites were located in Gadsden County, Florida, (30.3° N and 84.4° W) in soils characterized as kandiudults with low organic matter and pH values near 6.0 (Table 1). Soils were comprised of mostly sand, with silt and clay contents ranging from 9.3 to 12.6% and 5.7 to 10.2%, respectively. Sites CAR and JAS were located on commercial farms with a history of severe epidemics of bacterial wilt of tomato, caused by *Pseudomonas solanacearum* (Smith) Smith.

Treatments. Treatments consisted of soil solarization, fumigation with a 67:33 mixture of methyl bromide:chloropicrin applied at 448 kg/ha, solarization plus fumigation, and a fallow control and were arranged in a randomized complete block design. At the JAS site, the fumigant was applied twice within a 4-hr period because of difficulties in covering the treated areas with polyethylene film after the first application. Treatments were replicated three times at the CAR site and four times at the JAS and QCY sites.

Individual plots were 9 m wide and 30.5 m long. A 25-μm thick green polyethylene film (AEP Industries, Hackensack, NJ) containing additives that selectively reduced transmission of photosynthetically active radiation (PAR) was used in solarization and fumigation treatments. The film used in 1992 had transmission values of 40.3% for PAR and 62.6% for total solar radiation, and that used in 1993 had transmission values of 19.0% for PAR and 50.0% for total solar radiation. Reflectance values for both films were less than 8%. Sheets of film were 3 m wide and sealed together with glue to cover the entire 9-m width of a plot.

Prior to treatments, sites were deep-plowed and cultivated. Soil water matric potential at the time that treatments were applied ranged from −2 kPa at the CAR site to −25 kPa at the JAS site (Table 1). Treatments were applied on 19 June 1992 at the CAR site, 7 June 1993 at the QCY site, and 18 June 1993 at the JAS site. Polyethylene film was removed from fumigation treatments after 48 hr. Polyethylene film was removed from the solarization treatments after 32 days at the CAR site, 46 days at the JAS site, and 49 days at the QCY site. Hourly temperature changes in bare and solarized soil were monitored at depths of 5, 15, and 25 cm, using thermocouple sensors connected to an electronic data logger (Omnidata, Logan, UT). Ambient air temperature and daily precipitation totals were obtained from the National Weather Service Reporting Station 3SSW, located within 18 km of all three sites.

Solar heating under the photoselective polyethylene film used in the 1993 sites and under a clear polyethylene film was compared at the QCY site. A 9-m^2 sheet

Florida Experimental Station Journal Series R-03827.

Accepted for publication 12 September 1994.

of clear, UV-stabilized, low-density polyethylene film with a thickness of 50 μm (Polyon Barkai, Kibbutz Barkai, Israel) was placed adjacent to a 9-m^2 sheet of the photoselective film. Hourly soil temperatures were monitored over a 2-wk period at depths of 5, 15, and 25 cm in the center of each plot.

Table 1. Characteristics of field soils at the time of solarization and fumigation treatments

Site	pH	Soil moisture[a]	Percent organic matter	Percent sand-silt-clay	Soil class
CAR	5.9	14%, −2 kPa	1.1	77-13-10	Kandiudult[b]
QCY	6.0	11%, −8 kPa	1.4	85-9-6	Kandiudult
JAS	6.1	7%, −25 kPa	0.7	84-9-7	Kandiudult

[a]Percent water content and soil water matric potential.
[b]An Ultisol with profiles similar to Paleudults but containing higher amounts of kaolinitic clay.

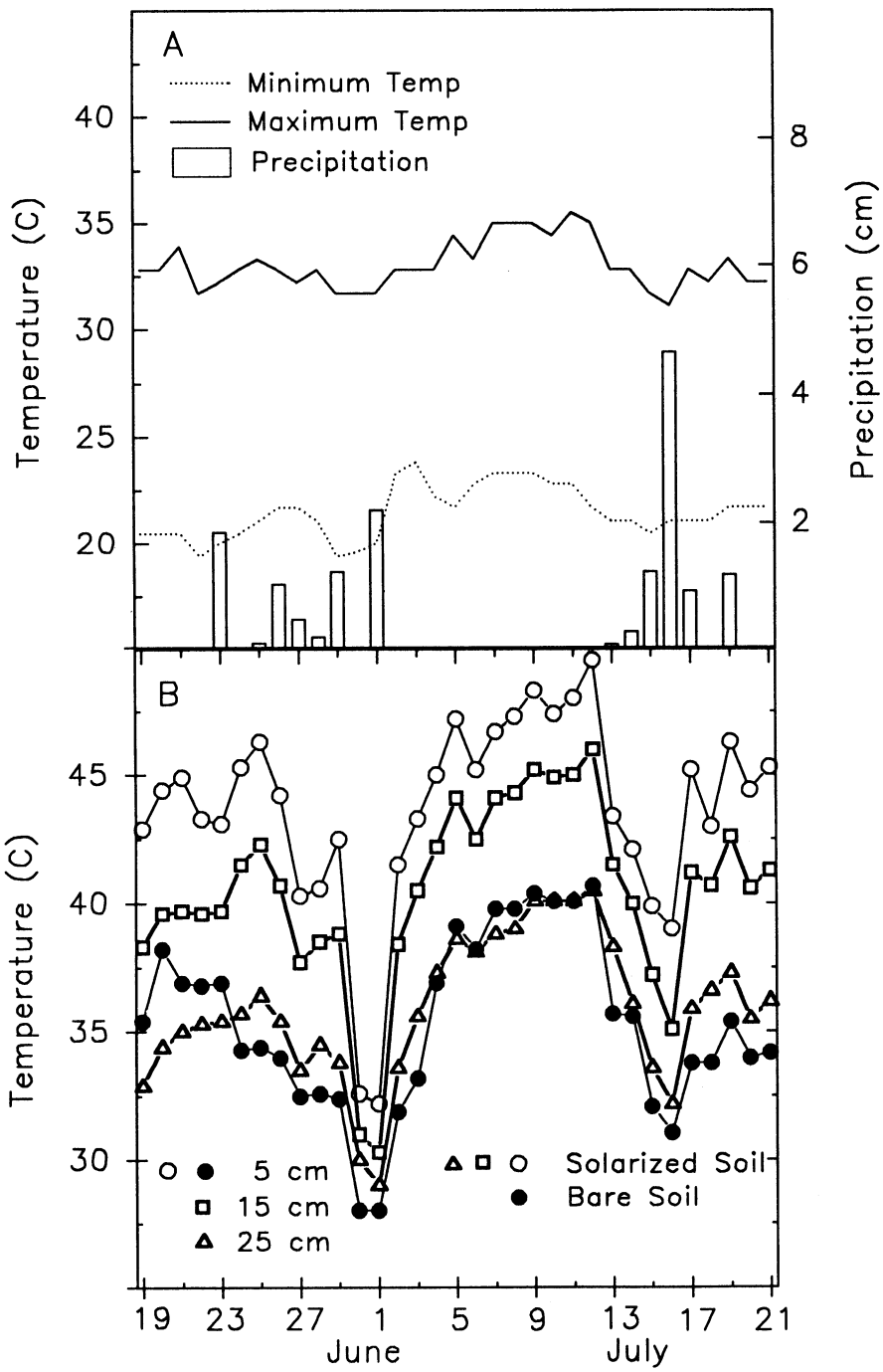

Fig. 1. Summary of temperature and precipitation at the CAR site in 1992: **(A)** Daily precipitation totals and minimum and maximum ambient temperatures and **(B)** daily maximum temperatures at three depths in solarized treatments and at one depth in bare soil.

Plant pathogens. Strain 1B of *Pseudomonas solanacearum*, isolated from an infected tomato plant in Gadsden County and characterized as race 1, biovar 3 (3), was streaked onto nutrient broth yeast extract agar and incubated for 48 hr at 27 C. Following incubation, bacterial suspensions were diluted with sterile tap water to 5.0×10^8 cfu/ml (OD_{600nm}= 0.77) and 0.3-ml aliquots were added to 5-cm^2 bags. Each bag contained 3 g of pasteurized soil adjusted to a moisture content of −10 kPa to make a final inoculum preparation of 5.0×10^7 cfu/g of soil. Bags were constructed from 0.2-μm-diameter Versapor membranes (Gelman Sciences, Ann Arbor, MI) and Arclad S-5913 adhesive (Adhesives Research, Glen Rock, PA).

Fusarium oxysporum Schlechtend.: Fr. f. sp. *radicis-lycopersici* W.R. Jarvis & Shoemaker, isolated from a tomato plant with symptoms of Fusarium crown rot in Collier County, Florida; *F. o. lycopersici* (Sacc.) W.C. Snyder & H.N. Hans. race 3, isolated from a tomato plant with symptoms of Fusarium wilt in Gadsden County; and *Phytophthora nicotianae* Breda de Haan var. *parasitica* (Dastur) G.M. Waterhouse, isolated from a citrus root in Polk County, Florida, were each grown on V8 juice agar at 25 C in petri plates. Inoculum of each fungus was produced on an autoclaved mixture of 100 g of wheat seed and 100 ml of deionized water in a 1-L flask. Three 3-mm disks of a 7-day-old colony of each fungus were added to each of three flasks of wheat seed. The flasks were maintained at 25 C for 14 days; the infested seed was shaken vigorously every 3 days to ensure uniform growth of the fungi. After 14–21 days, 0.2 g of colonized wheat seed was added to separate bags containing 3 g of pasteurized soil at −10 kPa matric potential. Bags were constructed from 3-μm Versapor membranes and Arclad adhesive as described previously.

Separate bags containing each pathogen were buried at depths of 5, 15, 25, and 35 cm in each replicate plot prior to application of treatments. Inoculum containing *F. o. lycopersici* was not buried at the CAR site. Bags were recovered upon completion of the solarization treatments, and soil was plated on a medium selective for *P. solanacearum* (4), *Phytophthora* spp. (26), and *F. oxysporum* (20) to determine the inoculum density.

Data analysis. Inoculum density counts were log-transformed ($\log_{10}[x + 1]$) and subjected to analysis of variance by a general linear models procedure (31). Significance of main effects and interactions were performed with F tests ($P \leq 0.05$). The effects of treatments at various depths in the soil were examined by 95% confidence intervals constructed from the mean square error obtained in the analysis of variance.

RESULTS

Effect of soil solarization on soil temperature. In 1992, 15.4 cm of precipitation was received during the 32-day solarization period, with rain events occurring on 13 days (Fig. 1A). The maximum ambient temperature was 35.6 C, recorded on 12 July. In the solarized plots, the maximum soil temperatures were 49.5, 46, and 40.5 C at depths of 5, 15, and 25 cm, respectively (Fig. 1B). Maximum temperatures recorded in bare soil were 40.7, 38.2, and 35.6 C at depths of 5, 15, and 25 cm, respectively. Two periods of intermittent temperature reduction, from 30 June to 1 July and from 14 July to 16 July, were observed. A total of 9.6 cm, or 62% of the precipitation received during the entire solarization period, fell during these two periods. Although weed populations were high in areas surrounding the plots, no weeds emerged from the soil under the solarization film during the 32-day period.

At the QCY site, 28.1 cm of precipitation was received during the 49-day solarization period, with rain events occurring on 23 days (Fig. 2A). In the solarized plots, the maximum soil temperatures were 47.4, 43.0, and 41.5 C at depths of 5, 15, and 25 cm, respectively (Fig. 2B). Maximum temperatures recorded in bare soil were 40.5, 37.4, and 35.3 C at depths of 5, 15, and 25 cm, respectively. Yellow nutsedge (*Cyperus esculentus* L.) was observed growing through the polyethylene film in the solarization plots. The polyethylene film at the QCY site was damaged by cattle on 12 June, and holes in the mulch were repaired on 16 June.

In 1993, 22.0 cm of precipitation was received during the 46-day solarization period at the JAS site, with rain events occurring on 21 days. The maximum ambient temperature was 36.7 C, recorded on 8 and 11 June. In the solarized plots, the maximum soil temperatures were 49.5, 43.8, and 40.8 C at depths of 5, 15, and 25 cm, respectively. Maximum temperatures recorded in bare soil were 43.8, 38.9, and 36.5 C at depths of 5, 15 and 25 cm, respectively.

At a 5-cm depth, the JAS site had the highest accumulation of hours in which soil temperatures were greater than 37, 40, and 43 C (Table 2). At a 15-cm depth, the JAS site had the highest accumulation of hours above 37 and 40 C, whereas the CAR site had the highest accumulation above 43 C. At a 25-cm depth, the QCY site had the highest accumulation of hours above 37 and 40 C. Temperatures above 43 C were not obtained at a 25-cm depth.

Maximum soil temperatures under the clear film were 2, 1.3, and 1 C higher at 5, 15, and 25 cm depths, respectively. Thermal accumulation above thresholds of 37, 40, and 43 C were higher under the clear film (Table 3). Differences in accumulation of hours above 40 C were larger at 15-cm depths than at 5- or 25-cm depths.

Effect of soil solarization on survival of plant pathogens. Soil treatment had a significant effect on survival of pathogens at each site (Table 4). The depth at which inoculum was buried had a significant effect on survival of *P. solanacearum* in two sites, *F. o. lycopersici* in one site, and *Phytophthora nicotianae* in all sites. Placement of inoculum did not significantly affect survival of *F. o. radicis-lycopersici*. A significant interaction between treatment and depth was observed for *P. solanacearum, Phytophthora nicotianae*, and *F. o. lycopersici* but not for *F. o. radicis-lycopersici*.

Soil solarization reduced *P. solanacearum* to undetectable levels at a 5-cm depth and significantly reduced survival at 15 cm in the JAS site (Fig. 3). Soil solarization also significantly reduced survival of *P. solanacearum* at a 5-cm depth in the other two sites. Fumigation did not affect survival in the CAR site but significantly affected survival in the QCY site at 15-, 25-, and 35-cm depths. Additional reductions in

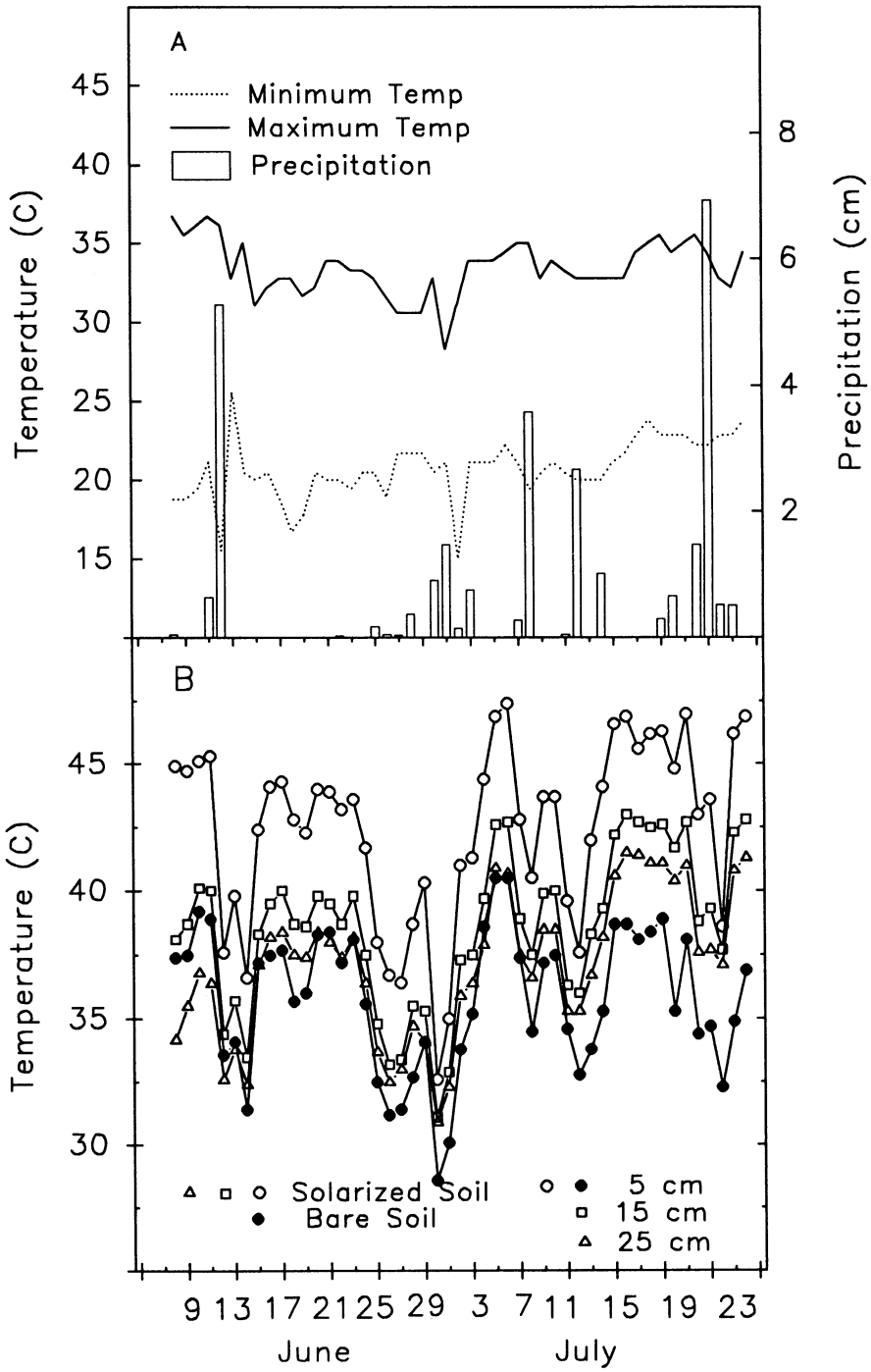

Fig. 2. Summary of temperature and precipitation at the QCY site in 1993: **(A)** Daily precipitation totals and minimum and maximum ambient temperatures and **(B)** daily maximum temperatures at three depths in solarized treatments and at one depth in bare soil.

survival of *P. solanacearum* were observed in both sites when fumigation was combined with soil solarization. In the JAS site, the two applications of fumigant dramatically reduced survival of *P. solanacearum*.

Soil solarization reduced *Phytophthora nicotianae* to undetectable levels at 5- and 15-cm depths in the JAS site and significantly reduced survival at a depth of 25 cm (Fig. 4). Soil solarization also significantly reduced survival at 5- and 15-cm depths in the other sites. Fumigation resulted in nearly complete eradication to depths of 35 cm in all sites.

Soil solarization significantly reduced survival of *F. o. radicis-lycopersici* at a 5-cm depth in two sites (Fig. 5). Fumigation significantly reduced survival down to 35 cm in all three sites.

Soil solarization significantly reduced survival of *F. o. lycopersici* at a 5-cm depth in one site (Fig. 6). Fumigation significantly reduced survival at all four depths but did not eradicate the pathogen in the QCY site.

Table 2. Thermal accumulation in soil solarization treatments[a]

Site	Depth (cm)	Duration (days)	Cumulative hr above: 37 C	40 C	43 C
CAR	5	32	244	172	86
	15	32	215	94	29
	25	32	79	7	0
QCY	5	49	293	184	83
	15	49	216	51	0
	25	49	148	32	0
JAS	5	46	331	258	180
	15	46	257	111	7
	25	46	130	11	0

[a]Soil solarization was performed using a low-density polyethylene film that reduced transmission of photosynthetically active radiation.

Table 3. Thermal accumulation under clear and photoselective low-density polyethylene films[a]

Film	Depth (cm)	Cumulative hr above: 37 C	40 C	43 C
Clear	5	127	97	69
	15	113	56	0
	25	68	0	0
IRT	5	119	87	55
	15	97	37	0
	25	43	0	0

[a]IRT film reduces transmission of photosynthetically active radiation.

DISCUSSION

Soil temperatures in solarization plots were increased by as much as 9, 8, and 5 C over temperatures in bare soil at depths of 5, 15, and 25 cm, respectively. Although solarization periods were 14–17 days longer in 1993, maximum temperatures and thermal accumulation at 15-cm depths were greater in 1992 (Fig. 1, Table 2). The increases in temperature and heat accumulation in 1992 were attributed to a combination of higher soil moisture prior to treatments and greater light transmission values of the polyethylene film. Temperature maxima of soils under clear polyethylene film are known to increase with increasing soil moisture content (22). Higher transmission values of the film used in 1992 permitted more solar radiation to reach the soil but did not adversely affect weed growth. Germination of yellow nutsedge under the film was widespread in 1993 but negligible in 1992, even though nutsedge was present at the 1992 site. Greater soil moisture in 1992 may have enhanced the transfer of heat to tubers.

Except at a 5-cm depth, the maximum soil temperatures achieved in this study were within the range of temperatures reported in other studies. At a 5-cm depth, the maximum temperature achieved was 49.5 C, which is several degrees lower than the 52–53 C temperatures reported from Israel (11,17). At a 15-cm depth, the maximum soil temperature of 46.0 C was within the 44–52 C maximum temperatures reported from California (14,32), Florida (24,28), and Israel (17). Comparison of soil temperatures between clear and photoselective film indicated that additional increases in the maximum temperatures of 1–2 C can be obtained with the clear polyethylene film. However, the benefits from suppression of weed growth under the photoselective film may outweigh any additional gains in soil temperatures.

The main difference between soil heating patterns in arid and humid climates is the day-to-day variation in maximum soil temperatures. In 1992, three cycles of elevated soil temperatures were evident and corresponded to two extended periods of overcast conditions with inter-

Table 4. Analysis of variance for the effects of soil disinfestation treatments and depth of inoculum on the survival of four soilborne pathogens

Site	Pathogen	Significance levels (*P*) of sources of variation: Treatment	Depth	Interaction
CAR	*Pseudomonas solanacearum*	<0.01	<0.14	<0.79
QCY	*P. solanacearum*	<0.01	0.03	0.10
JAS	*P. solanacearum*	<0.01	<0.01	<0.01
CAR	*Phytophthora nicotianae*	<0.01	<0.01	<0.01
QCY	*P. nicotianae*	<0.01	<0.01	<0.01
JAS	*P. nicotianae*	<0.01	<0.01	<0.01
CAR	*Fusarium oxysporum* f. sp. *radicis-lycopersici*	<0.01	0.49	0.68
QCY	*F. o. radicis-lycopersici*	<0.01	0.97	0.81
JAS	*F. o. radicis-lycopersici*	<0.01	0.23	0.23
QCY	*F. o. lycopersici*	<0.01	0.02	0.25
JAS	*F. o. lycopersici*	<0.01	0.08	0.01

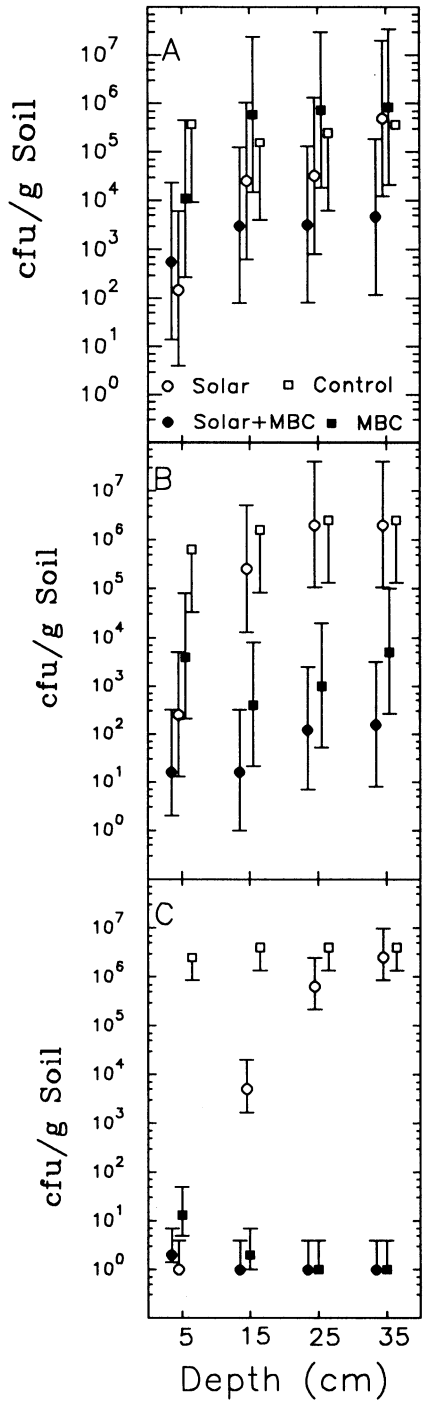

Fig. 3. Means and 95% confidence intervals for the effect of soil disinfestation treatments on *Pseudomonas solanacearum* at various depths: **(A)** CAR site, **(B)** QCY site, and **(C)** JAS site. Solar = solarization, MBC = fumigation, Solar + MBC = solarization and fumigation, control = fallow treatment.

mittent precipitation lasting several days. A different set of environmental conditions developed in 1993, where more rain events occurred over shorter durations, resulting in larger day-to-day fluctuations in the daily maximum temperatures (Figs. 2 and 3).

The thermal decline of soilborne organisms during solarization depends upon both the soil temperature and the exposure time (6). In 1992, 51 hr were accumulated above 40 C at a 15-cm depth (Table 2). During the same 32-day period in 1993, 44 and 56 hr were accumulated above 40 C at the QCY and JAS sites, respectively. In North Carolina, solarization treatments performed over a 35-day period produced 201 cumulative hours at 10-cm depths and 52 hr at 20-cm depths (30).

In Israel, soil solarization reduced populations of *F. o. lycopersici* by 94–100% at a 5-cm depth, 67–100% at a 15-cm depth, and 54–74% at a 25-cm depth (17). Comparisons with results in this study cannot be made without inclusion of information on quantitative changes in inoculum density. For example, reductions in *F. o. lycopersici* from 588,844 propagules per gram (ppg) of soil

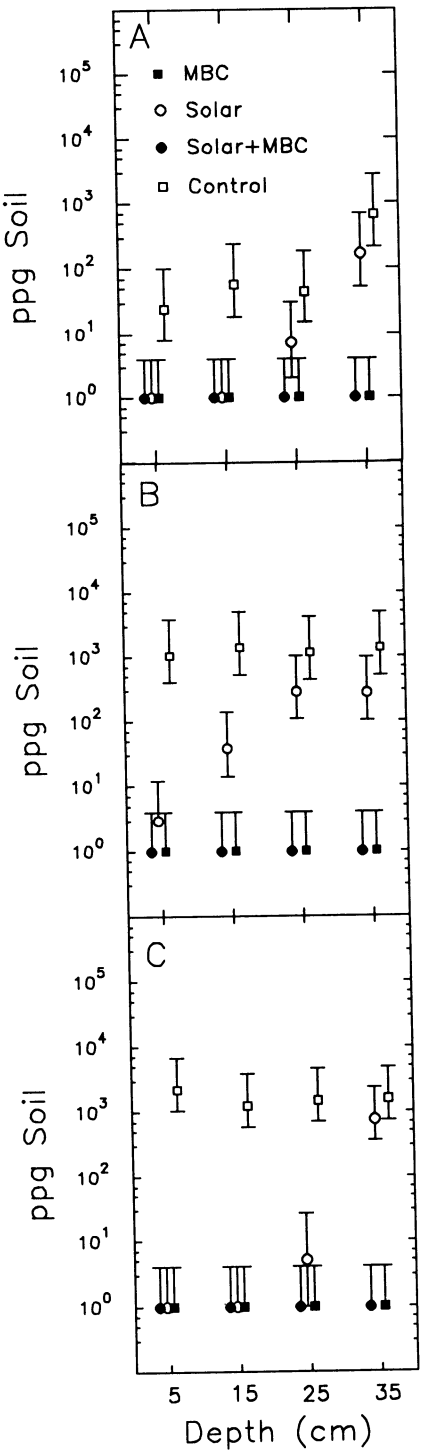

Fig. 4. Means and 95% confidence intervals for the effect of soil disinfestation treatments on *Phytophthora nicotianae* at various depths: **(A)** CAR site, **(B)** QCY site, and **(C)** JAS site. Solar = solarization, MBC = fumigation, Solar + MBC = solarization and fumigation, control = fallow treatment.

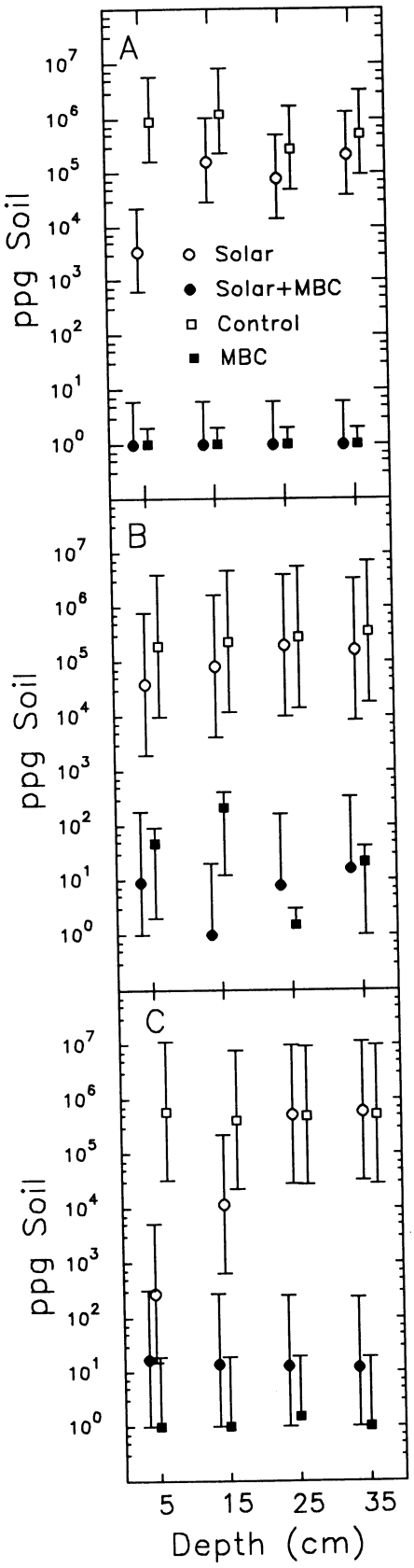

Fig. 5. Means and 95% confidence intervals for the effect of soil disinfestation treatments on *Fusarium oxysporum* f. sp. *radicis-lycopersici* at various depths: **(A)** CAR site, **(B)** QCY site, and **(C)** JAS site. Solar = solarization, MBC = fumigation, Solar + MBC = solarization and fumigation, control = fallow treatment.

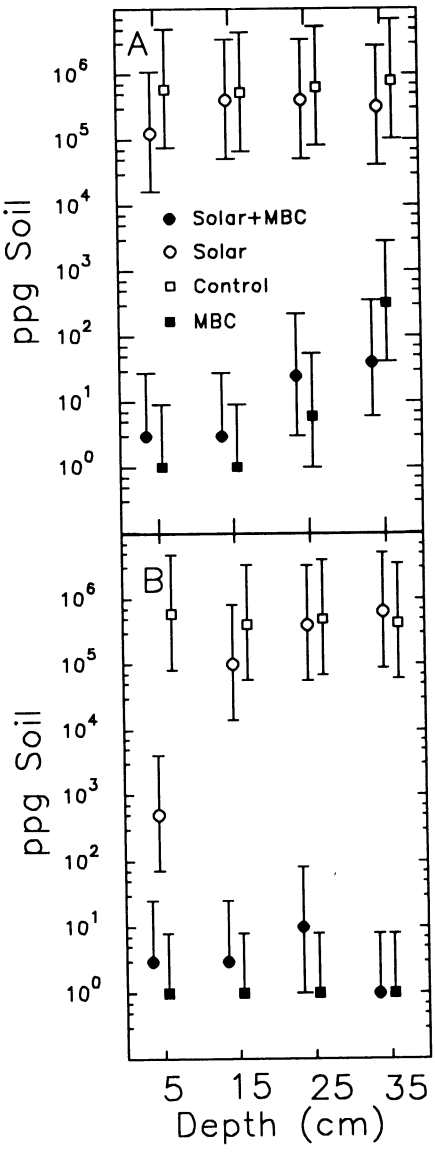

Fig. 6. Means and 95% confidence intervals for the effect of soil disinfestation treatments on *Fusarium oxysporum* f. sp *lycopersici* at various depths: **(A)** QCY site and **(B)** JAS site. Solar = solarization, MBC = fumigation, Solar + MBC = solarization and fumigation, control = fallow treatment.

in control plots to 537 ppg of soil in solarization plots occurred at a 5-cm depth in the JAS site (Fig. 6). Using the formula of Katan et al (17), this corresponded to a 99.9% reduction. While this reduction is impressive, it may not be below the threshold required to cause disease. It should be noted that inoculum levels prior to application of treatments were greater than 10^6 ppg of soil and reflected a worse-case scenario in which a grower would apply treatments immediately after harvest of a field with a high incidence of Fusarium wilt or Fusarium crown rot.

Phytophthora nicotianae was the most sensitive organism to soil solarization treatments. Previous studies have shown that other species of *Phytophthora* are also sensitive to temperatures achieved by soil solarization (12,14,15,34). While soil solarization treatments did not perform as well on *Phytophthora nicotianae* as they did on other *Phytophthora* species, significant ($P \leq 0.05$) and in some cases complete reductions did occur to a 25-cm depth (Fig. 4).

Fumigation with methyl bromide: chloropicrin was very effective against the fungal pathogens but produced mixed results against *P. solanacearum*. Methyl bromide has little effect on bacterial populations in soil (21,29) and does not provide season-long control of bacterial wilt of tomato (7). Chloropicrin can markedly depress bacterial populations (21,29), but the effect on bacterial wilt is erratic, with season-long control obtained in some studies (7,18) but not in others (7,25). Considerably higher silt and clay contents in the CAR site (Table 1) may have restricted movement of chloropicrin and reduced the efficacy. The pronounced reduction of *P. solanacearum* at the JAS site was due possibly to the extra application of methyl bromide: chloropicrin (896 kg/ha).

Reductions in populations of plant-pathogenic bacteria by soil solarization have been documented (32,33). In the southeastern United States, symptoms of bacterial wilt rarely develop when populations of *P. solanacearum* are less than 2.5×10^4 cfu/g of soil (7,19,27), while infested tomato fields often contain much higher populations of *P. solanacearum* at a depth of 30 cm (23). In this study, reductions of *P. solanacearum* below 2.5×10^4 cfu/g of soil were achieved at 5- and 15-cm depths only. Thus, it is unlikely that the reductions achieved by soil solarization alone will be sufficient to control bacterial wilt of tomato. Solarization of soil in greenhouses in Japan failed to control bacterial wilt of tomato even though soil temperatures were higher than those achieved in this study (13).

A combination of soil solarization and fumigation reduced populations of *P. solanacearum* to levels below 2.5×10^4 cfu/g of soil in all three sites. When a susceptible cultivar of tomato was planted in the CAR site, the incidence of bacterial wilt was reduced from 36% in control plots to 6% in plots treated with both soil solarization and fumigation (5). Synergistic effects between soil solarization and chemical or organic amendments that resulted in additional reductions of pathogen populations have been observed for other soilborne pests (8–10). These results are especially encouraging for future tomato production in North Florida where bacterial wilt is a major disease.

ACKNOWLEDGMENTS

We thank AEP Industries Inc. for solarization film; Adhesives Research Inc. for tape; H. Dankers, S. Lee, P. Rayside, and B. Loy for technical assistance; the Gadsden County Tomato Growers Association for financial assistance; and J. Katan for critical review of this manuscript.

LITERATURE CITED

1. Anonymous. 1993. The biologic and economic assessment of methyl bromide. USDA NAPIAP April.
2. Anonymous. 1993. Florida agricultural facts. Fla. Dep. Agric. Consum. Serv.
3. Chellemi, D. O., Dankers, H. A., Olson, S. M., Hodge, N. C., and Scott. J. W. 1994. Evaluation of bacterial wilt resistant tomato genotypes using a regional approach. J. Am. Hortic. Soc. 119:325-329.
4. Chellemi, D. O., Mitchell, D. J., and Barkdol, A. W. 1992. Effect of composted organic amendments on the incidence of bacterial wilt of tomato. Proc. Fla. State Hortic. Soc. 105:364-366.
5. Chellemi, D. O., Olson, S. M., Scott, J. W., Mitchell, D. J., and McSorley, R. 1993. Reduction of phytoparasitic nematodes on tomato by soil solarization and genotype. J. Nematol. 25(suppl.):800-805.
6. DeVay, J. E. 1991. Historical review and principles of soil solarization. Pages 1-15 in: Soil Solarization. J. E. DeVay, J. J. Stapleton, and C. L. Elmore, eds. FAO Plant Prot. Prod. Pap. 109.
7. Enfinger, J. M., McCarter, S. M., and Jaworski, C. A. 1979. Evaluation of chemicals and application methods for control of bacterial wilt of tomato transplants. Phytopathology 69:637-640.
8. Frank, Z. R., Ben-Yephet, Y., and Katan, J. 1986. Synergistic effect of metham and solarization in controlling delimited shell spots of peanut pods. Crop Prot. 5:199-202.
9. Gamliel, A., and Stapleton, J. J. 1993. Effect of chicken compost or ammonium phosphate and solarization on pathogen control, rhizosphere microorganisms, and lettuce growth. Plant Dis. 77:886-891.
10. Gamliel, A., and Stapleton, J. J. 1993. Characterization of antifungal volatile compounds evolved from solarized soil amended with cabbage residues. Phytopathology 83:899-905.
11. Grinstein, A., Katan, J., Abdul Razik, A., Zeydan, O., and Elad, Y. 1979. Control of *Sclerotium rolfsii* and weeds in peanuts by solar heating of the soil. Plant Dis. Rep. 63:1056-1059.
12. Hartz, T. K., DeVay, J. E., and Elmore, C. L. 1993. Solarization is an effective soil disinfestation technique for strawberry production. HortScience 28:104-106.
13. Horiuchi, S. 1991. Solarization for greenhouse crops in Japan. Pages 16-27 in: Soil Solarization. J. E. DeVay, J. J. Stapleton, and C. L. Elmore, eds. FAO Plant Prot. Prod. Pap. 109.
14. Juarez-Palacios, C., Felix-Gastelum, R., Wakeman, R. J., Paplomatas, E. J., and DeVay, J. E. 1991. Thermal sensitivity of three species of *Phytophthora* and the effect of soil solarization on their survival. Plant Dis. 75:1160-1164.
15. Kaewruang, W., Sivasithamparam, K., and Hardy, G. E. 1989. Use of soil solarization to control root rots in gerberas (*Gerbera jamesonii*). Biol. Fertil. Soils 8:38-47.
16. Katan, J., and DeVay, J. E. 1991. Soil solarization: Historical perspective, principles and uses. Pages 23-37 in: Soil Solarization. J. Katan and J. E. DeVay, eds. CRC Press, Boca Raton, FL.
17. Katan, J., Greenberger, A., Alon, H., and Grinstein, A. 1976. Solar heating by polyethylene mulching for the control of diseases caused by soilborne pathogens. Phytopathology 66:683-688.
18. Kelman, A. 1953. The bacterial wilt caused by *Pseudomonas solanacearum*. N.C. Agric. Exp. Stn. Tech. Bull. 99.
19. Kelman, A., and Sequeira, L. 1965. Root-to-root spread of *Pseudomonas solanacearum*. Phytopathology 55:304-309.
20. Komada, H. 1975. Development of a selective medium for quantitative isolation of *Fusarium oxysporum* from natural soil. Rev. Plant Prot. Res. 8:114-125.
21. Ladd, J. N., Brisbane, P. G., Butler, J. H. A., and Amato, M. 1976. Studies on soil fumigation—III. Effects on enzyme activities, bacterial numbers and extractable ninhydrin reactive compounds. Soil Biol. Biochem. 8:255-260.
22. Mahrer, Y., Naot, O., Rawitz, E., and Katan, J. 1984. Temperature and moisture regimes in soils mulched with transparent polyethylene. Soil Sci. Soc. Am. J. 48:362-377.
23. McCarter, S. M., Dukes, P. D., and Jaworski, C. A. 1969. Vertical distribution of *Pseudomonas solanacearum* in several soils. Phytopathology 59:1675-1677.
24. McSorley, R., and Parrado J. L. 1986. Application of soil solarization to Rockdale soils in a subtropical environment. Nematropica 16:125-140.
25. Melton, T. A., and Powell, N. T. 1991. Effects of two-year crop rotations and cultivar resistance on bacterial wilt in flue-cured tobacco. Plant Dis. 75:695-698.
26. Mitchell, D. J., and Kannwischer-Mitchell, M. E. 1992. *Phytophthora*. Pages 31-38 in: Methods for Research on Soilborne Phytopathogenic Fungi. L. L. Singleton, J. D. Mihail, and C. M. Rush, eds. American Phytopathological Society, St. Paul, MN.
27. Nesmith, W. C., and Jenkins, S. F., Jr. 1983. Survival of *Pseudomonas solanacearum* in selected North Carolina soils. Phytopathology 73:1300-1304.
28. Overman, A. J. 1985. Off-season land management, soil solarization and fumigation for tomato. Soil Crop Soc. Fla. Proc. 44:35-39.
29. Ridge, E. H. 1976. Studies on soil fumigation—II. Effects on bacteria. Soil Biol. Biochem. 8:249-253.
30. Ristaino, J. B., Perry, K. B., and Lumsden, R. D. 1991. Effect of solarization and *Gliocladium virens* on sclerotia of *Sclerotium rolfsii*, soil microbiota, and the incidence of southern blight of tomato. Phytopathology 81:1117-1124.
31. SAS Institute. 1988. SAS/STAT User's Guide. 6.03 ed. SAS Institute, Cary, NC.
32. Stapleton, J. J., and DeVay, J. E. 1982. Effect of soil solarization on populations of selected soilborne microorganisms and growth of deciduous fruit tree seedlings. Phytopathology 72:323-326.
33. Tjamos, E. C., Antoniou, P., and Panagopoulos, C. G. 1992. Control of bacterial canker of tomato by application of soil solarization. (Abstr.) Phytopathology 82:1076.
34. Wicks, T. J. 1988. Effect of solarization on the control of *Phytophthora cambivora* in almond and cherry. Aust. J. Exp. Agric. 28:539-545.