Efficacy of Solarization and Cabbage Amendment for the Control of *Phytophthora* spp. in North Florida

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ABSTRACT

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The effects of soil solarization with or without cabbage leaf amendments on the survival of *Phytophthora* spp. were evaluated in several North Florida soils. Soil temperature under solarization treatments reached a maximum of 47°C at a 10-cm depth, but only 41°C at 25 cm. Solarization with a clear, gas-impermeable film was as effective as methyl bromide in reducing populations of *P. nicotianae* at a 10-cm depth but had no effect on populations at a depth of 25 cm. Populations of *P. capsici* after solarization with either a clear, low-density polyethylene or a clear, gas-impermeable film were similar to methyl bromide treatment at the 10-cm depth, while at the 25-cm depth, no reduction in populations was observed. Incorporation of cabbage into the soil at a rate of 6.6 to 8.9 kg/m² did not enhance the effectiveness of solarization in reducing populations of either *Phytophthora* sp.

Additional keywords: *Brassica oleracea* var. *capitata*, chloropicrin, nonchemical control, organic amendment

Phytophthora nicotianae (syn. = *P. parasitica*) and *Phytophthora capsici* are economically important soilborne plant pathogens with wide host ranges (1). Diseases caused by these pathogens, such as damping-off, root rot, blight, and fruit rot, may limit production of several important crops (6,28). These *Phytophthora* spp. are capable of surviving in the soil for long periods of time in the absence of host plants and when weather conditions are not favorable for disease initiation and development (6). Thus, the main strategies used by growers to reduce losses due to these pathogens, especially at the early stages of plant development, are preplant soil fumigation with methyl bromide and postplant application of fungicides.

The implication of methyl bromide as an ozone depleting substance has prompted a search for alternatives for use in the control of soilborne plant pathogens. Soil solarization has been used in areas with arid climates for the management of soilborne diseases of high-value crops (2,12,14,15,17,35). Soil solarization is a hydro-

thermal process in which moist soil is covered with transparent plastic and exposed to sunlight, allowing it to heat to temperatures that are lethal to many plant pathogens, insects, and weed seeds (38). The effectiveness of solarization depends on soil color and structure, soil moisture, air temperature, length of day, and intensity of sunlight (38). Solarization has reduced populations of *Fusarium* spp. (2,16,33,37,38), *Phytophthora* spp. (2,12,13,27,31,32,38), *Pythium ultimum* (7,9,21,35,38,40,41), *Verticillium dahliae* (10,12,16,33,35,38), and *Rhizoctonia* sp. (11,19,23,35,38). However, disease management is not always observed following population suppression. For example, Stapleton and Garza-Lopez (41) reported a reduction in the population of *Macrophomina phaseolina* that did not result in less disease in the indicator crop. Other soilborne pathogens that have not been controlled by soil solarization include *Fusarium oxysporum* f. sp. *radicis-lycopersici*, *Plasmodiophora brassicae*, *Pythium aphanidermatum*, and *Sclerotium rolfsii* (2,38).

Success of solarization for the control of plant diseases is closely associated with a combination of high ambient temperatures, maximum solar radiation, and optimum soil moisture (14–17,38,39,41). Regions where high summer temperatures coincide with the rainy season, such as in the southeastern United States, may have less potential for successful solarization because the cooling effect of frequent rain showers and the extended cloud cover reduce the

solar radiation captured under the plastic tarp (2). Soil solarization has been used with varying degrees of success, however, in the southeastern United States to manage *Rhizoctonia solani*, *Didymella bryoniae*, *Fusarium* spp., and *P. nicotianae* (2,19,20). Populations of *P. nicotianae* were reduced to undetectable levels in soil depths of up to 15 cm in three sites in North Florida; however, reduction in populations below 25 cm in depth was noted in only one site (2). In contrast, methyl bromide nearly eradicated the pathogen at depths of up to 35 cm. Control of *Fusarium* spp. by soil solarization was limited to the top 5 cm of the soil, and no control was achieved at some sites (2). Keinath (19) found that the number of organic fragments colonized by *R. solani* was lower in solarized than in nonsolarized soils, but control of belly rot of pickling cucumber with solarization was not as effective as treatment with the fungicide chlorothalonil.

The type of plastic used for solarization may also influence soil solarization (5,25,38). For example, thin polyethylene sheets (25 µm) were more effective than thick sheets (50 to 100 µm) for the transmission of solar radiation to the soil (38), and a film of coextruded polyethylene plus ethylene vinyl acetate (thermoplast) was more effective than a clear low-density polyethylene film in raising soil temperatures and in trapping gases used for fumigation (25). Similarly, Chellemi et al. (3) found that a gas-impermeable film, consisting of a polyamide core sandwiched between two layers of polyethylene, was more effective than a coextruded, white-on-black film for the reduction of populations of *Paratrachodorus minor* and *Cricconemella* spp., and in the control of *Fusarium* wilt on tomatoes.

Soil solarization alone may not be consistently effective for the control of soilborne pathogens. In such cases, soil amendments have been used to enhance the performance of solarization (9,20,37). Cruciferous residues, due to their high content of isothiocyanates and aldehydes (glucosinolate degradation products), have been suggested as amendments for use in combination with solarization (26). Cabbage leaf debris is the primary amendment that has been studied in combination with soil solarization (20,37,38).

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Gamliel and Stapleton (8) characterized the antifungal volatiles from cabbage residue during solarization. The kinds of volatiles released from heated and nonheated soils differed, and the concentration of volatiles peaked during the first 2 weeks of heating. Spores of *P. ultimum* and sclerotia of *S. rolfii* failed to germinate after exposure to cabbage volatiles for 20 days. The use of a crucifer amendment associated with sublethal heating (38°C) reduced germination of *P. ultimum* and *S. rolfii* in vitro (40). It is possible that the major benefits of soil amendment with crucifer residues are associated with high but not lethal temperatures, when the heat alone is not sufficient to inactivate the pathogen; however, this aspect of the use of cabbage amendment has not been explored fully.

Cabbage amendments reduced populations of *F. oxysporum* f. sp. *conglutinans*; however, the association of solarization with the amendment was the most effective treatment for the control of this pathogen (37,38). High concentrations of cabbage amendment had no effect on the subsequent cabbage crop, but phytotoxicity was observed when tomato seedlings were transplanted into the treated soil.

The objective of this study was to evaluate the effects of soil solarization and cabbage amendment on the survival of *P. nicotianae* and *P. capsici* under field conditions in North Florida.

MATERIALS AND METHODS

Solarization sites. In 1994, two sites were selected in commercial tomato production fields where control of soilborne pathogens had been achieved previously through the use of a preplant application of methyl bromide plus chloropicrin. Site 1 was in Decatur County, Georgia. Site 2 was in Gadsden County, Florida. In 1996, two experiments were conducted at the University of Florida North Florida Research and Educational Center in Gadsden County on soils that had been weed fallow for several years. Soil types at all locations were Orangeburg or Tifton loamy fine sands (siliceous, thermic), with pH values ranging from 5.0 to 6.6 (Table 1).

Inoculum production. Inoculum of *P. nicotianae* was produced in 250-ml flasks containing 20 g of wheat seeds and 30 ml of deionized water (autoclaved twice at a 24-h interval). Four 5-mm agar plugs of actively growing mycelium of isolate Pn21

from a 4- to 7-day-old clarified V8 juice agar plate were transferred to each flask (30). The flasks were incubated at 25°C in the dark for 1 month and were shaken twice a week to ensure uniform growth of the isolate. Oospores of *P. capsici* were produced by inoculating similarly prepared 250-ml flasks of wheat seeds with three 5-mm agar plugs of actively growing mycelium of each of two isolates of compatible mating types (Cp25 and Cp26). The flasks were incubated at 25°C in the dark for 2 months and shaken twice a week to encourage uniform growth of both isolates. Isolate Pn21 was originally obtained from periwinkle, and isolates Cp25 and Cp26 were obtained from watermelon in South Florida. All isolates are maintained in the collection of *Phytophthora* spp. of the Plant Pathology Department, University of Florida, Gainesville.

Inoculum of *P. nicotianae* or *P. capsici* was incorporated into the soil by mixing 200 mg of shredded, infested wheat seeds with 3 g of soil. Nonpasteurized soils from sites 1 and 2 were used in 1994, and the soils were infested 2 days before the samples were taken to the field. To encourage augmented formation of chlamydospores or oospores in the two experiments in 1996, pasteurized soil from site 1 was infested with *P. nicotianae* and incubated at 18°C for 10 days, or with *P. capsici* and incubated at 25°C for 10 days, before its placement in the field tests. In all tests, each 3-g sample was enclosed in a 25 cm² nylon envelope (3-µm-pore size; Versapor 3000, Gelman Sciences, Inc., Ann Arbor, MI), and the envelopes were buried in the soil at depths of 10 and 25 cm just before application of the solarization treatments.

Survival of the spores at the end of the solarization experiments was determined by plating infested soil from the envelopes on a medium selective for pythiaceus fungi (PARPH) (30).

Solarization experiments. At site 1, six treatments were arranged in a randomized complete block. Treatments were replicated four times and included a 30-µm-thick, clear, gas-impermeable film (Bromotec film; Bromotec, Lawson Mardon Packaging, United Kingdom), a 30-µm-thick, coextruded white-on-black, low-density polyethylene (LDPE) film (white-on-black film; Edison Plastics, Lee Hall, VA), and each film with or without cabbage residue (*Brassica oleracea* var. *capitata* L. cv. Constanza) incorporated into the soil at a rate of 8.0 kg/m². A tarp treatment (white-on-black film) fumigated with a 67:33 formulation of methyl bromide:chloropicrin at 39.2 g/m² and a non-tarped treatment were used as controls.

At site 2, six treatments were arranged in a randomized complete block. Treatments included a 30-µm-thick, clear, LDPE film (Polydak film, Polyon Barkai Ltd., Kibutz Barkai, Israel); the Bromotec film; each film with or without cabbage residue (cv. Constanza) incorporated into the soil at a rate of 6.6 kg/m²; and the two controls.

For tests 1 and 2 at site 3, six treatments were arranged in a randomized complete block design with four replicates. Treatments included the Bromotec film, the white-on-black film, each film with or without cabbage residue incorporated into the soil at a rate of 8.9 kg/m² for test 1 and 8.1 kg/m² for test 2, and the two controls.

At sites 1 and 2, each replicate plot consisted of a single raised bed (0.20 × 0.90 × 20 m) prepared according to standard commercial production practices. Row orientation was north to south. Preplant fertilizer was broadcast into the beds at 212 kg of N, 65 kg of P, and 212 kg of K per ha, and drip irrigation tubing was placed 5 cm beneath the soil on sites 1 and 2 prior to covering with plastic. At site 3 for tests 1 and 2, each replicate plot consisted of one raised 0.20 × 0.90 × 4.0 m bed prepared according to standard commercial production practices; row orientation was north to south. No fertilizer was applied and no irrigation tubing was placed on the beds.

Cabbage was grown and harvested in the plots at sites 1 and 2, and the residue was spread over the plots on 23 and 24 May 1994. Beds were prepared, the nylon envelopes containing the inoculum were placed in the soil, and the fumigant and plastic were applied on 3 June 1994 at site 1. Solarization was terminated on 22 July 1994, after 49 days, and the nylon envelopes were removed for determination of survival. At site 2, beds were prepared, the nylon envelopes containing the inoculum were buried, and the fumigant and plastic were applied on 15 June 1994; solarization was terminated on 2 August 1994, after 48 days, and the nylon envelopes were removed. For tests 1 and 2 at site 3, cabbage was harvested from a commercial field in Hastings, Florida; head and wrapper leaves were shredded and spread over the plots on 12 June for test 1, and on 19 June 1996 for test 2. Beds were prepared, two sets of nylon envelopes containing the inoculum were placed in each plot, and the fumigant and plastic were applied on 21 June and 28 June 1996, respectively. Solarization was terminated with the removal of the last nylon envelopes on 6 and 13 August 1996, after 45 days, for tests 1 and 2, respectively.

Daily ambient temperature data were

Table 1. Characteristics of field soils at the time of solarization

Site	Year	pH	Soil water potential [†] (–kPa)	Organic matter (%)	Sand-silt-clay (%)	Soil class
1	1994	6.6	5	1.1	84.0-6.0-10.0	Kandiudult [‡]
2	1994	5.1	15	0.5	88.5-4.5-7.0	Kandiudult
3, test 1	1996	5.0	5	1.0	80.4-11.1-8.5	Kandiudult
3, test 2	1996	5.0	50	1.2	82.8-10.0-7.2	Kandiudult

[†] Estimated by the gravimetric method with oven drying, prior to initiation of the experiment, and transformed to matric potential.

[‡] Ultisol with profiles similar to paleudults but containing higher amounts of kaolinitic clay.

obtained from a weather station at the North Florida Research and Educational Center, in Quincy, located approximately 25 km from sites 1 and 2, while daily precipitation amounts were recorded at each site. In 1994, soil temperatures were monitored in site 2 at depths of 10 and 25 cm using thermocouple sensors connected to an electronic data logger (OmniData International, Logan, UT). For the two tests at site 3, daily rainfall and ambient temperature data were recorded at the site. In 1996, temperature changes were monitored in test 1 at 10- and 25-cm depths in the soil using thermocouple sensors connected to an electronic data logger (Campbell Scientific, Logan, UT). Temperature data were compared with the thresholds of 41, 44, and 47°C, as determined by Coelho (4). The first two thresholds (41 and 44°C) represent average temperatures reached at a depth of 10 cm in soils under solarization; the last one (47°C) represents the optimum temperature for solarization in North Florida.

Statistical analysis. Survival data for each pathogen were log-transformed [$\ln(\text{ppg} + 1)$] prior to analysis. Analysis of variance was performed with a repeated-measures procedure from SAS (SAS Institute, Cary, NC) release 6.11 for personal computers. Survival of *P. nicotianae* or *P. capsici* under each treatment was compared using Tukey's honestly significant difference procedure.

RESULTS

Environmental conditions. Environmental conditions varied from year to year (Fig. 1). The 1994 season was characterized by above-average precipitation and below-average temperatures. In 1996, precipitation was below average and temperatures were near 30-year averages. Soil moisture at the beginning of the solarization treatments varied with experiment, ranging from -5 to -50 kPa (Table 1). Precipitation occurred on 61% of the days of the solarization period at site 1, 65% of the days at site 2, 42% of the days in test 1 at

site 3, and 47% of the days in test 2 at site 3 (Table 2).

During the 48 days of solarization at site 2, temperatures exceeded 41°C on 2 days at the 10-cm soil depth in the nontarped treatment; 41°C was exceeded on 15 days in the Polydak film treatment and on 20

days in the Bromotec film treatment (Table 3). Temperatures exceeded 44°C at the 10-cm depth on 9 days under the Polydak film and on 13 days under the Bromotec film. Temperatures were above 47°C for 1 day and 3 days under the Polydak and the Bromotec films, respectively. At the 25-cm

Fig. 1. Maximum and minimum air temperature and precipitation recorded at each site during the solarization period, from 1994 and 1996. (A) Solid arrows indicate beginning and end of solarization at site 1; open arrows indicate beginning and end of solarization at site 2. (B) Solid arrows indicate beginning and end of solarization in test 1 at site 3; open arrows indicate beginning and end of solarization in test 2 at site 3.

Table 2. Environmental conditions during solarization periods

Site	Year	Precipitation (mm)	Number of days		
			Solarization period	Precipitation occurred	Ambient temperature $\geq 35^\circ\text{C}$
1	1994	460	49	30	0
2	1994	384	48	31	0
3, test 1	1996	232	45	19	6
3, test 2	1996	264	45	21	4

Table 3. Temperature profiles during soil solarization at site 2 and at site 3, test 1

Site ^w /test	Depth (cm)	Nontarped ^x			White-on-black			Polydak film			Bromotec film		
		41°C	44°C	47°C	41°C	44°C	47°C	41°C	44°C	47°C	41°C	44°C	47°C
Number of days above threshold													
Site 2	10	2	0	0	NT ^y	NT	NT	15 ^z	9	1	20	13	3
	25	0	0	0	NT	NT	NT	0	0	0	0	0	0
Site 3/1	10	1	0	0	0	0	0	NT	NT	NT	32	24	10
	25	0	0	0	0	0	0	NT	NT	NT	1	0	0
Number of hours above threshold													
Site 2	10	4	0	0	NT	NT	NT	63	25	2	82	42	7
	25	0	0	0	NT	NT	NT	0	0	0	0	0	0
Site 3/1	10	1	0	0	0	0	0	NT	NT	NT	225	125	24
	25	0	0	0	0	0	0	NT	NT	NT	4	0	0

^a Site 2 was solarized for 48 days in 1994; site 3 was solarized for 45 days in test 1.

^x Nontarped = untreated soil; white-on-black = 30- μm -thick, coextruded white-on-black, LDPE film; Polydak film = 30- μm -thick, clear, LDPE film; Bromotec film = 30- μm -thick, clear, gas-impermeable film.

^y NT = not tested.

^z Temperatures measured during the first 42 days of solarization.

depth, temperatures never reached the 41°C threshold under any of the treatments. Maximum temperatures attained in site 2 at the 10-cm depth under nontarped soil, the Polydak film, and the Bromotec film were 41.5, 47.3, and 48.5°C, respectively. At the 25-cm depth, maximum temperatures were 34.6, 37.9, and 38°C under nontarped soil, the Polydak film, and the Bromotec film, respectively. The mean soil temperature change during the day is illustrated in Figure 2A and B.

During the 45 days of solarization at site 3 for test 1, maximum temperatures attained at the 10-cm depth under nontarped

soil, white-on-black film, and the Bromotec film were 41.1, 39.0, and 49.1°C, respectively. At the 25-cm depth, maximum temperatures were 37.4, 37.5, and 41.4°C under nontarped soil, white-on-black film, and the Bromotec film, respectively. Under the Bromotec film, at the 10-cm depth, maximum temperature was above 41°C for 32 days, above 44°C for 24 days, and above 47°C for 10 days; while at the 25-cm depth, 41°C was exceeded on only 1 day (Table 3). Temperatures at the 10-cm depth in the nontarped treatment exceeded 41°C on 1 day during the solarization period, and under the white-on-

black film, temperatures never reached that threshold. The mean temperature change during the day is illustrated in Figure 2C. Soil temperature changes for test 2 at site 3 were not monitored.

At the 10-cm depth, the highest accumulation of hours in which soil temperatures were greater than 41, 44, and 47°C was observed in test 1 at site 3 (Table 3). The lowest accumulation of hours was observed at site 2. At site 2, it was possible to compare the accumulation of hours above the given thresholds under the various solarization films. Under the Bromotec film at the 10-cm depth, temperatures were above 41, 44, and 47°C for 82, 42, and 7 h, respectively; while under the Polydak film the accumulation was of 63, 25, and 2 h, respectively. In the nontarped treatment and at the 25-cm depth of all treatments, temperatures never reached the 44°C threshold.

Survival of *Phytophthora nicotianae*.

At site 1, propagules of *P. nicotianae* were not recovered from the nontarped or the methyl bromide treatments. Propagules were also not recovered at the 10-cm depth in the Bromotec treatment, with or without cabbage, after 49 days of solarization (Table 4). The highest level of survival was observed under the white-on-black polyethylene film at 10 cm of depth with or without cabbage amendment. At the 25-cm depth under the Bromotec film, propagules were recovered at the same levels as in the white-on-black film treatment.

At site 2, contaminants from the soil limited recovery of *P. nicotianae* in all treatments, except under the Polydak film at the 10-cm depth (data not shown).

Propagules of *P. nicotianae* were recovered from all treatments in test 1 at site 3, except from soil treated with methyl bromide; however, there were no significant differences among the treatments (Table 4).

Trends similar to those observed in site 1 were observed in test 2 at site 3 (Table 4). Only methyl bromide eliminated the pathogen from the soil. The Bromotec film was the next best treatment at the 10-cm depth, regardless of the cabbage amendment, for reduction of the population of the pathogen; however, at the 25-cm depth, the Bromotec film was not effective, and more than 200 propagules of *P. nicotianae* survived per g of soil. Similar results were observed under the white-on-black film, with or without cabbage amendment, and in the nontarped treatment. Survival in the nontarped treatments in tests 1 and 2, in contrast to the lack of survival in site 1, could have been due to the change in the procedure for soil infestation from that used for site 1; chlamydospores were already present at the beginning of the experiments in the soil prepared for tests 1 and 2, but not for site 1 (4).

Samples removed after 17 days of solarization in tests 1 and 2 at site 3 demonstrated that the pathogen survived for a

Fig. 2. Average hourly temperatures at 10 and 25 cm deep during the solarization period. Temperatures were measured in the untreated soil (nontarped), under the white-on-black, low density polyethylene film (white-on-black), under the Polydak film, and under the Bromotec film. (A) site 2 at the 10-cm depth (1994). (B) site 2 at the 25-cm depth. (C) site 3, test 1 (1996).

short duration, except in the methyl bromide treatment (Table 4). Increases in populations were observed in test 2, mostly at the 25-cm depth, in the nontarped, Bromotec and white-on-black treatments after 45 days of solarization. Significant differences were observed at the 10-cm depth between the two sampling dates under the Bromotec film; the population of *P. nicotianae* dropped to levels comparable to those in the methyl bromide treatment at the end of the solarization period.

Survival of *Phytophthora capsici*. At site 1, propagules were not recovered at the 10-cm depth after treatment with methyl bromide, the Bromotec film, or the Bromotec film combined with cabbage (Table 5). Low levels of survival at the 25-cm depth under the methyl bromide treatment, the Bromotec film, and the Bromotec film combined with cabbage were obtained, but the levels were not different from the same treatments at the 10-cm depth. Greatest survival was observed under the white-on-black film at the 10-cm depth, regardless of cabbage amendment, and in the nontarped treatment.

At site 2, survival was significantly reduced, in comparison to the nontarped treatments, with methyl bromide, Bromotec film, and Polydak film with or without cabbage at 10 cm, and with Bromotec film plus cabbage at 25 cm (Table 5).

DISCUSSION

Soil solarization is a pasteurization process dependent on solar energy to heat the soil and kill pathogens. Effective pasteurization occurs when soil sustains temperatures that are lethal to the fungal propagules infesting the soil, such as those reported in arid climates (18,34,38). However, in climates where cloud cover and rainfall interrupt the heating process of the soil, maximum temperatures recorded tend to be lower, and control of

soilborne plant pathogens is not as effective (2,3,19,29).

Temperature changes were monitored in two of the four experiments (site 2; and site 3, test 1). Inferences from site to site have to be made with caution, since soil color, proportion of sand, silt, and clay content, and soil moisture were different. Each of these factors can affect the temperature accumulation in soil, and when taken together could cause significant deviations in temperature from the patterns observed at the site where temperatures were actually measured. Because tests 1 and 2 at site 3 were only a few meters apart, with the same type of soil, any differences in temperature could be explained best by the change in moisture content. As

shown by Mahrer et al. (24), the higher the water content of the soil, the higher the maximum temperature. Thus, higher survival of the pathogens in test 2 could be explained by the lower moisture content of the soil.

P. nicotianae is believed to survive in root fragments and organic matter in the soil, or as chlamydospores free in the soil (6). Infested wheat seeds were selected for inoculum to favor the formation of chlamydospores in soil, simulating natural spore formation for field survival. Soil moisture also may have contributed to the variability in recovery of *P. nicotianae* among tests and sites. In test 1 at site 3, the plastic treatments were laid down after a week of frequent rains, with soil moisture

Table 5. Survival of *Phytophthora capsici* in the soil

Treatment ^w	Depth (cm)	Propagules per g of soil	
		Site 1	Site 2
Bromotec film	10	0.0 ^x a ^y	0.0 a
Bromotec film	25	1.5 ab	7.0 ab
Bromotec film + cabbage	10	0.0 a	0.4 a
Bromotec film + cabbage	25	1.2 ab	0.5 a
Polydak film	10	NT ^z	0.0 a
Polydak film	25	NT	11.2 ab
Polydak film + cabbage	10	NT	0.2 a
Polydak film + cabbage	25	NT	7.9 ab
White-on-black	10	84.6 c	NT
White-on-black	25	47.4 c	NT
White-on-black + cabbage	10	70.8 c	NT
White-on-black + cabbage	25	16.3 bc	NT
Methyl bromide	10	0.0 a	0.2 a
Methyl bromide	25	1.1 ab	0.9 a
Nontarped	10	33.4 c	33.9 b
Nontarped	25	63.0 c	25.6 b

^w Nontarped = untreated soil; methyl bromide = soil fumigated with methyl bromide:chloropicrin at 39.2 g/m²; white-on-black = soil solarized under a 30-μm-thick, coextruded white-on-black, LDPE film; Polydak film = soil solarized under a 30-μm-thick, clear, LDPE film; Bromotec film = 30-μm-thick, clear, gas-impermeable plastic film. Soil was either nonamended or amended with cabbage (+ cabbage) at 8.0 and 6.8 kg/m² at sites 1 and 2, respectively.

^x Weighted means ([exp{mean}] - 1).

^y Main effect means followed by the same letter do not differ according to Tukey's honestly significant difference procedure ($P \leq 0.05$); data were transformed to $\ln(\text{ppg} + 1)$ prior to analysis.

^z NT = not tested.

Table 4. Survival of *Phytophthora nicotianae* in the soil

Treatment*	Depth (cm)	Propagules/g of soil				
		Site 1 49 days	Site 3 - test 1		Site 3 - test 2	
			17 days	45 days	17 days	45 days
Bromotec film	10	0.0 ^y a ^z	2.0 a	0.4 a	544.6 b	4.4 a
Bromotec film	25	39.1 abc	4.1 a	2.1 a	168.0 b	202.3 b
Bromotec film + cabbage	10	0.0 a	2.7 a	0.9 a	52.5 b	1.0 a
Bromotec film + cabbage	25	7.2 ab	0.7 a	2.3 a	491.3 b	362.0 b
White-on-black	10	380.5 c	22.8 a	4.0 a	196.6 b	733.9 b
White-on-black	25	12.9 abc	16.3 a	0.9 a	186.4 b	697.8 b
White-on-black + cabbage	10	439.1 c	101.9 a	14.8 a	830.5 b	825.3 b
White-on-black + cabbage	25	44.9 bc	25.0 a	12.3 a	608.3 b	749.5 b
Methyl bromide	10	0.0 a	0.0 a	0.0 a	0.0 a	0.0 a
Methyl bromide	25	0.0 a	0.0 a	0.0 a	0.0 a	0.0 a
Nontarped	10	0.0 a	21.6 a	14.9 a	1,138.7 b	700.7 b
Nontarped	25	0.0 a	6.2 a	4.5 a	311.8 b	687.3 b

^x Nontarped = untreated soil; methyl bromide = soil fumigated with methyl bromide:chloropicrin at 39.2 g/m²; white-on-black = soil solarized under a 30-μm-thick, coextruded white-on-black, LDPE film; Bromotec film = soil solarized under a 30-μm-thick, clear, gas-impermeable plastic film. Soil was either nonamended or amended with cabbage (+ cabbage) at 80, 89, and 81 tons/ha at site 1, and for tests 1 and 2 at site 3, respectively.

^y Weighted means ([exp{mean}] - 1).

^z Main effect means followed by the same letter do not differ according to Tukey's honestly significant difference procedure ($P \leq 0.05$); data were transformed to $\ln(\text{ppg} + 1)$ prior to analysis.

very uniform throughout the soil profile. In test 2 at site 3, the week preceding the application of the plastic treatments was hot and dry, and irrigation was required to provide moisture for the solarization. These factors may have affected the results observed for the tests, especially in test 2, where higher numbers of surviving propagules were observed at greater depths. Since the solarization process depends on soil moisture for heat conduction, it is possible that temperatures did not rise as much in test 2 as in test 1 due to the lack of moisture. Indeed, the water status in test 1 (–5 kPa) was 10 times higher than that of test 2 (–50 kPa).

The absence of chlamydospores in the wheat seeds at the time of inoculum preparation, as observed microscopically in a squash mount, and a subsequent lack of survival of *P. nicotianae* in the nontarped treatments in 1994 prompted a search for methods that would augment the production of this type of inoculum (4). The highest number of chlamydospores was observed in pasteurized soil from site 1 after incubation at 18°C for 10 days; thus, inoculum was prepared in 1996 by infesting microwaved soil from site 1 and incubating it at 18°C for 10 days before burial in all of the test sites. After this change in inoculum preparation, *P. nicotianae* was recovered from the nontarped treatment (Table 4).

Solarization with Polydak or Bromotec film was effective in reducing populations of *P. nicotianae* at the 10-cm depth. At this depth, chlamydospore mortality was similar to that achieved by fumigation with methyl bromide. However, at the 25-cm depth, the populations recovered on dilution plates were similar to those in the nontarped or the white-on-black film controls. Clearly, solarization alone, or solarization with cabbage amendments, cannot be relied upon to eliminate *P. nicotianae* from soil under the conditions encountered in these tests. Chellemi et al. (2) also found that soil solarization alone reduced populations of *P. nicotianae* to undetectable levels at a depth of 15 cm; however, at the 25-cm depth, no differences in survival were observed between the solarized and the control treatments in two sites.

Although the same two isolates of *P. capsici* were used in all crosses to produce oospores for all tests, the numbers of oospores observed in wheat seeds were not consistent from year to year. The evaluation of survival of *P. capsici* also was hindered by the poor germination of propagules in the selective medium. Larkin et al. (22) compared different media for the germination of oospores of *P. capsici* and found that PARPH was the best medium for the study of this pathogen. However, in the present study, only approximately 1% of the oospores germinated in PARPH. Even with the low populations detected, *P. capsici* survived better in the nontarped treatments and under the white-on-black

film, regardless of the cabbage amendment. Control of this pathogen was most effective with methyl bromide, followed by the Bromotec and Polydak films at the 10-cm depth.

The failure of cabbage to affect the survival of either pathogen is contrary to observations of other researchers (20,37,38). It is probable that the differences observed are due either to amounts of amendment used or to the preparation of the cabbage amendment and its incorporation into the soil. For all of the field plots in the present study, cabbage was either chopped with a machete (1994) or shredded in a shredder (1996). In either case, the fragments were relatively large, and incorporation was done by disking the residue into the soil at the same time that the raised beds were being prepared, which may have led to an uneven distribution of the amendment in the soil profile. In contrast, Ramirez-Vilapudua and Munneke (37) used air-dried cabbage ground with a Wiley mill to a fine powder. This residue was incorporated into small amounts of soil, which were placed in plastic bags to be solarized. Further work by these authors (36) indicated that populations of *F. oxysporum* f. sp. *conglutinans* were reduced by the incorporation of cabbage into the soil at rates that were higher than those used in the experiments reported here. Keinath (20) found that gummy stem blight of watermelon was reduced in areas that received cabbage amendment and solarization; however, no information about the amount of residue incorporated into the soil was given. It also may be that the effectiveness of cabbage as a soil amendment is influenced by the drying process, and during the experiments reported here, rainfall during the drying time may have had a detrimental effect.

Although increased efficacy of soil solarization by cabbage amendment on the reduction of populations of *P. nicotianae* and *P. capsici* was observed, these reductions were not enough to eliminate the pathogens at the same depths as methyl bromide. Therefore, other alternatives to enhance the efficacy of soil solarization in North Florida must be found.

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