HORTSCIENCE 38(2):239–243. 2003.

Enhanced Production of *Brassica oleracea* Transplants Using Bed Solarization and Metam Sodium

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Additional index words. Brassicaceae, broccoli, *Fusarium oxysporum*, *Fusarium solani*, integrated pest management, kale, *Meloidogyne* sp., plant disease, soil solarization, seed-beds, transplant diseases, weeds, Bermuda

Abstract. **Experiments at two commercial farms in Bermuda tested the effectiveness of solarization of narrow beds alone and together with metam sodium (MS) to enhance in-field production of broccoli (*Brassica oleracea* L. var. *botrytis* L.) and kale (*B. oleracea* L. var. *acephala* DC.) transplants. Soil treatments of clear, low-density polyethylene (LDPE) mulch (25 μM), white LDPE mulch (25 μM) plus MS (702 L·ha^{-1}), and clear mulch plus MS were compared to bare soil. Mulches were applied and MS incorporated through rototiller cultivation 20 cm deep into 1.2-m-wide, flat seed-beds in the last week of June 1995. Mulches were maintained for 8 weeks. Either Broccoli 'Pirate' or kale 'Blue Curled Scotch' were seeded into transplant beds in Warwick and Devonshire parishes, respectively. Stand data was obtained for broccoli and kale 25 and 35 days, respectively, after seeding. Transplants were rated for root infection and biomass at 11 days (broccoli) or 31 days (kale) after seeding. In general, solarization was as effective as MS in suppression of soilborne pathogens of broccoli and kale plants. An additive effect on plant biomass was observed when solarization and MS were combined. All treatments significantly increased the establishment of broccoli plants and decreased root infection by *Rhizoctonia solani* in both crops. The incidence of *Fusarium* sp. was significantly decreased by all treatments in kale roots, and in broccoli by MS alone and in combination with solarization. Shoot fresh weight was significantly increased in kale by all treatments and in broccoli by solarization plus MS.**

Although agricultural activity in Bermuda is constrained due to limited land availability, small-scale farms contribute to the island's food supply. Cole crop production in Bermuda, including broccoli (*Brassica oleracea* L. var. *botrytis* L.), cabbage (*B. oleracea* L. var. *capitata* L.), cauliflower (*B. oleracea* L. var. *botrytis* L.), and kale (*B. oleracea* L. var. *acephala* DC.), occurs from August through May and comprises ≈20 ha annually. Local production accounts for up to 25% of total consumption of cole crops. Transplants of *Brassica oleracea* are traditionally produced in nonmulched seed-beds without preplant fumigation. (Metam sodium is used in mulched bed production of strawberry on the island). Reported soilborne pathogens of *Brassica* sp. in Bermuda include *Rhizoctonia solani* Kühn and *Sclerotinia sclerotiorum* (Lib.) de Bary, but disease incidence and crop loss data have not been well documented or are outdated (Waterston, 1947). Solarization is a low-impact management strategy that generally has been effective in reducing diseases caused by *Rhizoctonia*, but this technique has been more variable in management of other soilborne pests such as *Fusarium* sp. and root knot nematodes (*Meloidogyne* sp.) (McGovern and McSorley, 1997). In previous studies the combination of soil solarization with the fumigant metam sodium resulted in a synergistic reduction of delimited shell spot in peanut (a disease of unknown etiology), *Fusarium oxysporum* Schlectend.:Fr. f. sp. *radicis-lycopersici* W.R. Jarvis and Shoemaker in tomato, *F. oxysporum* Schlectend.:Fr. f. sp. *vasinfectum* (Atk.) W.S. Snyder & H.N. Hans., *Verticillium dahliae* Kleb. in cotton, and inoculum densities of *V. dahliae* and *Phytophthora cactorum* (Lebert & Cohn) J. Schrot. (Ben-Yephet et al., 1989; Frank et al., 1986; Hartz et al., 1993; McGovern et al., 1995). The objective of our research was to evaluate the ability of soil solarization, metam sodium (MS), and a combination of the two to enhance in-field production of broccoli and kale transplants in Bermuda.

Received for publication 29 Nov. 2001. Accepted for publication 5 June 2002. This research was supported by the Florida Agricultural Experiment Station, and approved for publication as Journal Series No.R-07374. We thank the Dept. of Agriculture, Fisheries & Parks, Government of Bermuda for support of this research, and the Atlantis Plastics Corp., Atlanta, Ga., for supplying and transporting plastic mulch.
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Materials and Methods

Experimental sites and treatments. The soils of Bermuda have not been officially classified but are relatively shallow, mostly alkaline, calcareous (volcanic origin), and have organic matter contents ranging from 3% to 6%. Commercial vegetable farms in Warwick (sandy loam) and Devonshire (silty loam) parishes, Bermuda were used to evaluate the effectiveness of three soil treatments in enhancing production of field-grown broccoli and kale transplants. The Warwick site had been continuously used for vegetable and herb production for several years, including rocquette (*Eruca vesicaria* L. Cav.) and coriander (*Coriandrum sativum* L.) the previous year. The Devonshire site had been previously used for vegetable transplant production, but had been fallowed the previous year because of the suspected build-up of root-knot nematodes. Irrigation for both farms was derived primarily from rainfall with some supplemental overhead irrigation; showers immediately preceding solarization ensured adequate soil moisture necessary for the process.

Treatments consisted of clear, low-density polyethylene (LDPE) mulch (25 μM; Atlantis Plastics Corp., Atlanta, Ga.), white LDPE mulch (25 μM) plus MS (Vapam, 702 L·ha^{-1}), and clear mulch plus MS. The experiments were initiated in Warwick and Devonshire on 28 and 29 June 1995, respectively. Treatments and a nontreated control (bare soil) were replicated six times at the Warwick farm using 1.2 × 9.3-m flat seed-beds arranged in a randomized complete-block design. A randomized complete-block design with three replications consisting of 1.2 × 10.4-m seed-beds was established at the Devonshire farm. Metam sodium was sprayed on the soil using a CO_2-powered sprayer through hand-held boom equipped with four hollow cone nozzles at a rate of 702 L·ha^{-1}, and incorporated through rotovation (rototiller cultivation) ≈20 cm deep. Following MS application, beds were immediately covered with either white mulch to test the effect of MS alone, or clear mulch to evaluate the combined effects of solarization and MS.

Daily maximum soil temperatures were monitored at 5, 15, and 30 cm in bare soil, and under white and clear mulch in mid afternoon (1430–1500 HR) at the Devonshire site by means of soil thermometers from 28 June through 25 Aug. Mulches remained intact until 26 Aug., after which time significant tearing due to hurricane damage occurred. The mulch was totally removed by 29 Aug. at both sites.

Seeding and plant data acquisition. The soil was rototilled to a depth of 20 cm, and broccoli 'Pirate' was seeded at ≈2 kg·ha^{-1} in transplant beds at the Warwick farm on 30 Aug. Damage resulting from the passage of another hurricane necessitated total reseeding and re-cultivation of beds on 5 Oct. at this site. Kale 'Blue Curled Scotch' was seeded in beds at the Devonshire farm on 15 Sept. in the same manner. Transplant establishment was assessed by counting the number of plants in a randomly selected 1-m-long section of each bed 25 d after seeding in Devonshire, and 35 d after seeding in Warwick. Weed coverage of beds was estimated using a 1 to 5 scale, where 1 = 0%, 2 = 1% to 25%, 3 = 26% to 50%, 4 = 51% to 75%, and 5 = 76% to 100% bed coverage on the same dates used to evaluate plant establishment. Fresh weights of roots and shoots of 10 randomly selected transplants per bed were obtained on 16 Oct. at both farms.

Soilborne pathogens. Infection frequency was evaluated on 16 Oct. using 5 of the 10 transplants sampled to obtain biomass data. The crown and roots of these plants were placed on 25% strength acidified potato dextrose agar (¼ APDA) after surface disinfestation in 0.5% NaOCl. Culture plates were examined after 24, 48, and 72 h to identify and enumerate fungal colonies. Because of large inter-treatment differences in root biomass, infection frequency by *R. solani* and *Fusarium* sp. was standardized by dividing the number of fungal colonies [colony-forming units (cfu)]/root by the average root weight (g) of the corresponding treatment replication. Pretreatment (background), posttreatment (preseeding), and final (end of experiment) soil samples for enumeration of root-knot nematodes (*Meloidogyne* sp.) by the sieving and centrifugation method (Jenkins, 1964) were collected on 22 June, 6 Sept., and 6 Dec. respectively. Pretreatment nematode sampling consisted of six 500-cm^3 subsamples which were taken from each field to a depth of 15 cm, pooled, and mixed. Posttreatment and final soil samples consisted of two cores from each plot that were processed as described above. Plant root systems were also examined for symptoms of disease and root-knot nematode damage prior to fungal isolation. Treatment means were separated by Tukey's Studentized Range (HSD) Test ($P \leq 0.05$) following analysis of variance (ANOVA).

Pathogenicity assay. Three-week-old seedlings of broccoli 'Green Giant' and 'George's Best', grown in 10.2-cm-diameter pots containing a peat-based medium, were used to test the pathogenicity of *F. oxysporum* isolated from a broccoli transplant grown at the Warwick farm. Six transplants of each cultivar were inoculated by pouring 50 mL of a conidial suspension (4×10^4 microconidia + macroconidia/mL) into each pot. An equal number of plants served as noninoculated controls. Plants were maintained at 25 °C under fluorescent lights using a 12-h photoperiod for 4 weeks. Thereafter, the fresh weights of roots and shoots were obtained, and the crown and roots of plants placed on ¼ APDA after surface disinfestation for reisolation of *F. oxysporum*.

Results

Soil temperatures. Weather conditions conducive to solarization prevailed during the soil treatment period; precipitation for July (9.24 cm) and August (16.6 cm) was only elevated by 4% and 10%, respectively, compared with historical norms (Dept. of Agr., Fisheries & Parks, 1995a, 1995b). Average maximum soil temperatures under clear mulch at 5, 15, and 30 cm were 48.2, 36.9, and 33.6 °C, respectively, and were higher than corresponding averages in nonmulched soil (33.6, 31.6, and 30.0 °C) (Fig. 1). Average maximum soil temperatures recorded under white mulch (42.0, 35.2, and 31.6 °C) were intermediate.

Plant establishment and biomass. All soil treatments produced increases in the establishment of broccoli transplants compared with nontreated soil (Table 1). However, broccoli transplants were more numerous in soil treated with MS alone than with a combination of solarization plus MS. The fresh weights of both roots and shoots of broccoli transplants were significantly increased compared to the control by solarization plus MS. (Both broccoli and kale transplants produced in nontreated plots were noticeably shorter than those produced

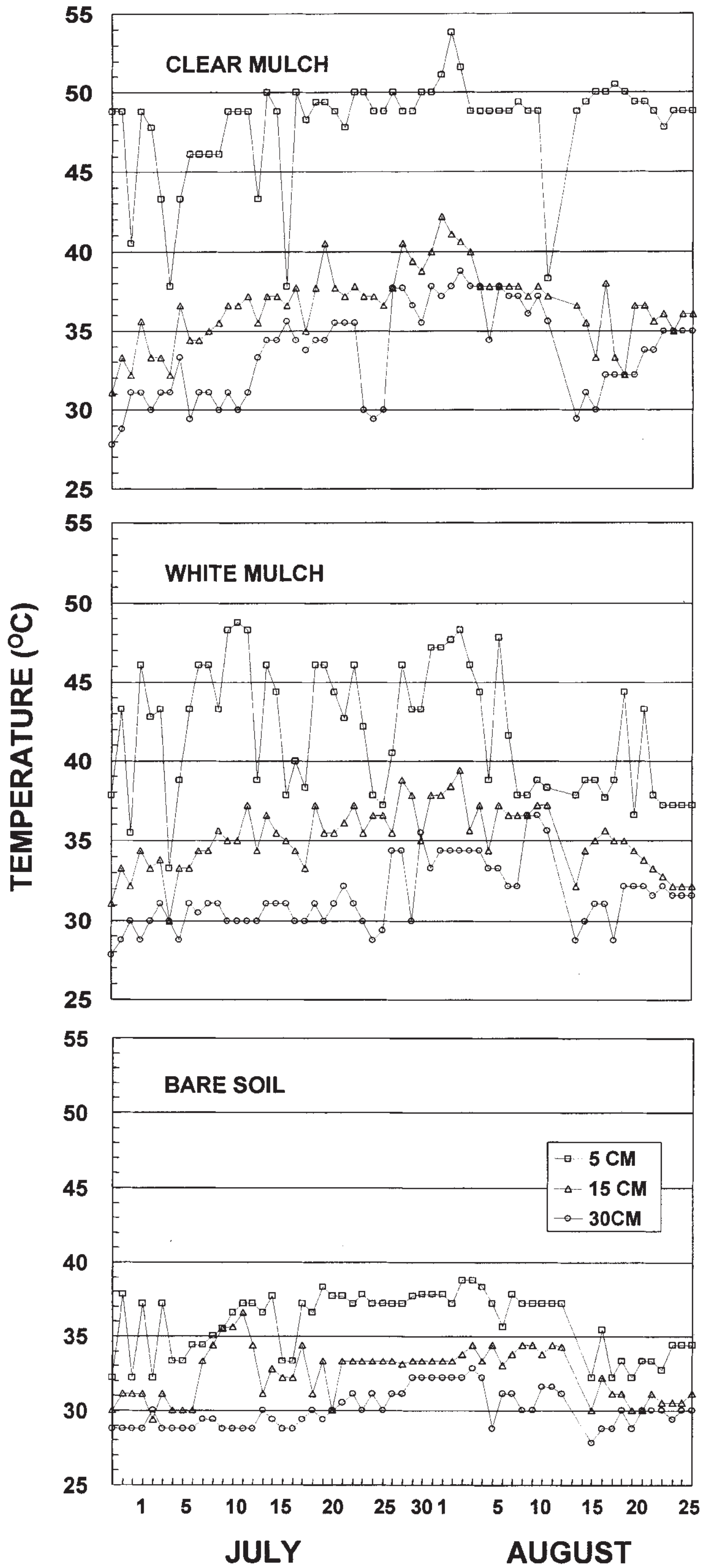

Fig. 1. Effect of mulch on soil temperature at Devonshire, Bermuda, at 5, 15, and 30 cm between 2:30 and 3:00 PM from 28 June through 25 Aug. 1995.

Table 1. Effect of soil solarization and metam sodium on plant establishment and growth, and on soil-borne pests in field-produced broccoli 'Pirate' transplants in Warwick, Bermuda.

Treatments	Plant estab. (no. plants/m²)	Shoot wt (g)	Root wt (g)	*Rhizoctonia solani* (cfu/g root)[z]	*Fusarium* sp. (cfu/g root)	*Meloidogyne* sp. preseeding (no./80 cm³ soil)	*Meloidogyne* sp. final (no./80 cm³ soil)	Weed rating (1–5)[y]
Control	127.3 c[x]	5.9 a	0.35 b[4]	8.3 a	4.4 a	8.3 a	0.0 a	2.8 a
Solarization	170.6 ab	6.3 a	0.46 ab	3.3 b	2.1 ab	0.6 b	0.0 a	2.2 a
Metam sodium (MS)	187.6 a	7.2 ab	0.47 ab	3.1 b	1.8 b	0.0 b	0.3 a	1.0 b
Solarization + MS	160.1 b	8.4 a	0.58 a	1.5 b	0.9 b	0.0 b	0.0 a	1.0 b
				ANOVA				
F values	9.27	3.99	3.24	7.99	3.65	15.81	1.00	18.69
P values	0.0031	0.034	0.060	0.003	0.044	0.003	0.454	<0.0001

[z]Infection frequency by *R.* solani and *Fusarium* sp. was standardized by dividing the number of fungal colony-forming units (cfu) by the average root weight of the corresponding treatment replication.
[y]Weed-coverage of beds was estimated using a 1 to 5 scale where 1 = 0%, 2 = 1% to 25%, 3 = 26% to 50%, 4 = 51% to 75%, and 5 = 76$ to 100% bed coverage.
[x]Means followed by different letters are significantly different by Tukey's Studentized Range (HSD) test ($P \leq 0.05$).

in treated soil.) Although none of the treatments statistically increased the establishment of kale transplants, each produced numerical increases (Table 2). All treatments significantly increased the fresh weight of kale shoots and roots, with the combination of solarization and MS producing a higher shoot biomass than solarization alone (Table 2).

Soilborne pathogens and weeds. Root systems did not generally vary in coloration but varied greatly in terms of mass; root and shoot systems from treated beds were noticeably larger and heavier, and appeared to have more feeder roots. *Rhizoctonia solani* and *Fusarium* sp., primarily *F. oxysporum* and *F. solani* (Mart). Sacc., were frequently isolated from the roots and crowns of both broccoli and kale transplants (Tables 1 and 2). Infection frequency (cfu/g root) of *R. solani* was significantly decreased by all treatments at both sites. Likewise, *Fusarium* infection in kale was decreased by all treatments, while MS alone and combined with solarization decreased *Fusarium* infection in broccoli.

Pretreatment sampling detected background populations of *Meloidogyne* sp. at a density of 17/80 cm³ soil at both experimental sites. All treatments significantly reduced the density of *Meloidogyne* sp. immediately prior to seeding at the Warwick farm, but populations of the nematode declined to very low levels in all plots by the end of the experiment (Table 1). *Meloidogyne* sp. had declined to undetectable levels by seeding at the Devonshire site (Table 2). Thereafter, populations of the nematode rebounded slightly in this field; *Meloidogyne* sp. was detected at very low levels in each control bed but in none of the treated beds by the completion of the experiment.

Weed coverage was moderate to high in the non-treated beds at both sites and consisted primarily of broadleaf plants. Galinsoga (*Galinsoga parviflora* Cav.), love grass (*Eragrostis* sp.), pigweed (*Amaranthus* sp.), purslane (*Portulaca oleracea* L.), wild mustard (*Brassica* sp.), and volunteers of rocquette and coriander were the most prevalent weeds at the Warwick farm, while galinsoga, pigweed, and purslane predominated at the Devonshire farm. Metam sodium and the combination of solarization and MS significantly reduced weed coverage at the Warwick farm (Table 1). Although all treatments were ineffective at the Devonshire site, the combination of solarization with MS was numerically the lowest (Table 2).

Pathogenicity assay. Inoculation of seedlings with conidia of *F. oxysporum* significantly reduced both shoot and root fresh weight in broccoli 'George's Best, but had no effect on the biomass of 'Green Giant' (Table 3). Inoculated plants of 'George's Best' were visibly shorter than non-inoculated plants. The frequency of *F. oxysporum* infection in both cultivars was comparable to levels observed in field-grown broccoli and kale transplants in Bermuda. One cfu of *F. oxysporum* was detected in the root system of two noninoculated 'George's Best' transplants, presumably due to splash contamination from adjacent inoculated plants.

Discussion

In general, we found soil solarization to be as effective as MS in increasing biomass and suppressing prevalent soilborne pathogens in field-grown *B. oleracea* transplants at both sites in Bermuda. Exceptions to this generalization were the failure of solarization alone to significantly reduce *Fusarium* infection of broccoli at the Warwick farm and infestation by weeds at the Devonshire farm. It is possible that some of the effectiveness of solarization and the other treatments against pathogens was negated by re-cultivation at the Warwick farm, through movement of nontreated soil into transplant root zones. However, additional soil cultivation could have aided in weed control at this site through physical destruction of newly emerging weeds. Differences in soil type between the two sites may have also led to variations in effectiveness through differential heating, water retention, or both (Katan, 1981; Stapleton and DeVay, 1986). Another source of variation between the two sites could have been the age at which the transplants were sampled.

Although solarization plus MS consistently produced the lowest infection frequencies by *R. solani* and *Fusarium* sp., we did not observe the increased benefit from this combination observed in other research (Ben-Yephet et al., 1989; Frank et al., 1986; McGovern et al., 1995; Porter et al., 1991). However, we did observe what appeared to be an additive effect of solarization and MS in consistent biomass increases. Combination of solarization with a broad-spectrum biocide such as MS may have the additional benefit of ensuring a degree of pathogen reduction during unexpectedly suboptimal periods for solarization. Use of solarization in rotation with fumigants or in combination with reduced rates of fumigants

Table 2. Effect of soil solarization and metam sodium on soilborne pests, plant establishment, and growth in field-produced kale 'Blue Curled Scotch' transplants in Devonshire, Bermuda.

Treatments	Plant estab. (no. plants/m²)	Shoot wt (g)	Root wt (g)	*Rhizoctonia solani* (cfu/g root)[z]	*Fusarium* sp. (cfu/g root)	*Meloidogyne* sp. preseeding (no./80 cm³ soil)	*Meloidogyne* sp. final (no./80 cm³ soil)	Weed rating (1–5)[y]
Control	68.8 a[x]	5.8 c	0.23 c	16.0 a	10.2 a	0.0	1.0 a	2.5 a
Solarization	80.4 a	11.9 b	0.39 b	5.4 b	6.2 b	0.0	0.0 b	3.5 a
Metam sodium (MS)	72.2 a	14.7 ab	0.61 a	3.4 b	5.0 b	0.0	0.0 b	3.5 a
Solarization + MS	75.4 a	17.0 a	0.51 ab	2.4 b	3.4 b	0.0	0.0 b	2.0 a
				ANOVA				
F values	0.450	29.29	33.43	15.95	17.97	---	>100	2.45
P-values	0.737	0.010	0.008	0.023	0.020	---	<0.0001	0.240

[z]Infection frequency by *R.* solani and *Fusarium* sp. was standardized by dividing the number of fungal colony-forming units (cfu) by the average root weight of the corresponding treatment replication.
[y]Weed coverage of beds was estimated using a 1 to 5 scale, where 1 = 0%, 2 = 1% to 25%, 3 = 26% to 50%, 4 = 51% to 75%, and 5 = 76% to 100% bed coverage, respectively.
[x]Means followed by different letters are significantly different by Tukey's Studentized Range (HSD) test ($P \leq 0.05$).

Table 3. Effect of infection by *Fusarium oxysporum* on root and shoot biomass in broccoli 'George's Best' and 'Green Giant'.

	George's Best			Green Giant		
Treatment	Shoot wt (g)	Root wt (g)	cfu/g root	Shoot wt (g)	Root wt (g)	cfu/g root
Noninoculated	12.9 a[z]	1.82 a	0.30 b	4.40 a	0.53 a	0.0 b
Inoculated	8.2 b	0.86 b	5.40 a	5.48 a	0.48 a	3.80 a
			ANOVA			
F values	4.72	6.35	>100	1.34	0.08	>100
P values	0.054	0.030	<0.0001	0.273	0.781	<0.0001

[z]Means followed by different letters are significantly different by ANOVA.

provides another approach to lessening the environmental impact of broad-spectrum biocides (Calabretta et al., 1991; Cebolla et al., 1995; Peachey et al., 2001; Porter et al., 1991).

Although reductions in root-knot nematode densities occurred at both sites with each of the treatments, low *Meloidogyne* populations prevented a thorough evaluation of their effectiveness. In separate research, we have observed that solarization using two layers of mulch is very effective against *Meloidogyne incognita* (Kofoid & White) Chitwood (McGovern et al., 1998). Variability of weed control by both solarization and MS observed in our research has been demonstrated in other studies (Abdallah, 2000; Gilreath et al., 2000; Marenco and Lustosa, 2000; Rotteveel et al., 1993; Vargas et al., 1993).

Temperatures that have been reported to rapidly (within 0.5 to 1.0 h) inactivate *Fusarium* sp. (55 to 65 °C) and *R. solani* (50 to 52.5 °C) only occurred or were approached in the upper soil strata under clear mulch (Bollen, 1985; Pullman et al., 1981). Other mechanisms in concert with thermal inactivation may have been responsible for the disease suppression and enhanced plant growth observed. In addition to direct thermal effects, it has been hypothesized that solarization may weaken plant pathogens through sublethal heating which may lead to decreased growth rate or virulence, decreased sporulation, delayed spore germination, increased susceptibility to biological control agents, etc. (Devay and Katan, 1991; Lifshitz et al., 1983; Stapleton and Devay, 1986). Buildup of volatile compounds, including nitrogenous substances, and thermotolerant pathogen antagonists in the soil have been suggested as other mechanisms for pathogen reduction by solarization (Stapleton and Devay, 1986; Stapleton et al., 1991). Keinath observed that increases in *Penicillium* sp. accompanied significant decreases in Rhizoctonia belly rot in cucumber in solarized soil (Keinath, 1995). It has also been suggested that increased plant growth following solarization may be the result of increased availability of mineral nutrients or increased activity of plant growth-promoting rhizobacteria (Gamliel and Katan, 1991; Grunzweig et al., 1999).

Solarization with clear mulch in narrow strips such as those used in this research has been reported to be less effective in pathogen reduction than mulching entire planting sites, including intervening drive-rows where narrow bed culture is practiced. This reduced efficacy has been attributed to the cooling "border effect" of the surrounding nonsolarized soil (Antoniou et al., 1995; Asworth and Gaona, 1982; Grinstein et al., 1995; Mahrer and Katan, 1981). Nevertheless, soil solarization of narrow beds ("row solarization") has been an effective management practice in other pathosystems (Chellemi et al., 1997; Hartz and Bogle, 1989; Hartz et al., 1993; Katan et al., 1980; Keinath, 1995; McGovern et al., 1995). It has been suggested that concentration of pathogen inocula in the upper soil layer lessens the border effect (Gullino et al., 1998); the relatively shallow soils we encountered may make this phenomenon possible for and relevant to solarization in Bermuda and similar settings. Row solarization would appear to have particular merit for soilborne pathogen reduction in short-term crops such as the cole transplants studied in this research, and for raised beds where whole-field solarization would be unsuitable because of water pooling due to frequent summer rainfall.

The broccoli transplant grower in Warwick has continued to use solarization as a routine preplant practice. Although no longer in business, the grower in Devonshire was able to successfully farm the experimental site for the first time in a number of years through the use of solarization and metam sodium. Following removal of a portion of the kale seedlings for transplanting elsewhere, he was able to take the remainder of the crop in treated plots to maturity. Our findings suggest that research evaluating the use of solarization alone and in combination with MS as a preplant practice for strawberry culture in Bermuda and other crops in areas with Caribbean-type climates would have merit.

Infection by *F. oxysporum* reduced root and shoot biomass in one of two broccoli cvs. tested similar to that observed in the field, indicating that the fungus may be involved in a disease complex with *R. solani* in this crop. Combined infection by *R. solani* and *F. oxysporum* and its control by soil solarization have also been observed in basil (*Ocimum basilicum* L.) (Gullino et al., 1998). Although preliminary, this apparent differential cultivar response suggests that resistance may serve as an additional component in an integrated approach to management of *F. oxysporum* in *B. oleracea* in Bermuda.

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