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Performance of Soil Solarization and Methyl Bromide in Sites Infested with Root-knot Nematodes

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Fumigation with methyl bromide has been a principal means of managing soilborne pest problems for many years. Interest in effective alternatives increased during the phase-out of methyl bromide, and will become more acute as existing stocks are depleted. Since it can reduce plant-parasitic nematode infestations, soil solarization could be a useful component in a nonchemical alternative program, but questions remain about its efficacy relative to methyl bromide. The performance of solarization and fumigation with methyl bromide:chloropicrin (50:50) were compared in snapdragon (*Antirrhinum majus* L.) cut flower crops in sites with a history of problems from root-knot nematodes (*Meloidogyne* spp.). In most instances, snapdragon plants exhibited lower levels of galling caused by root-knot nematodes following preplant fumigation than following solarization. Fumigation also resulted in increased plant height, but crop yield was unaffected, due to variability among plots. Following the solarization treatment with drenches of Biophos® did not improve results over solarization alone. Solarization was not as consistent as soil fumigation in reducing galling from root-knot nematodes. Although it can be useful in an integrated program as a non-chemical alternative to methyl bromide, solarization should be used with caution in sites with heavy pressure from root-knot nematodes.

Historically, methyl bromide has been the primary chemical of choice for managing soilborne pest problems in many countries including the United States, but its phase-out is leading to an urgent need for effective alternatives (Rosskopf et al., 2005; Schneider et al., 2003). A wide range of chemical alternatives are being examined, including other broad-spectrum soil fumigants (Obenauf, 2008). Nonchemical alternatives have received increased attention as well (Rosskopf et al., 2005), but some of these methods, such as crop cultivars with resistance to nematodes, are effective against only one group or even one species of soilborne pests (McSorley, 1998). Soil solarization has been used in many countries to manage soilborne pest problems for over 30 years (Katan, 1981; Katan et al., 1976). In this process, solar radiation passing through clear polyethylene is used to heat soil to temperatures that can be lethal to soilborne pests. Unlike many other nonchemical practices, it affects many different kinds of soilborne pathogens including fungi, bacteria, and plant-parasitic nematodes (Katan, 1981; McGovern and McSorley, 1997; Ostrec and Grubisic, 2003), and has been effective in managing weeds as well (Chase et al., 1998; Gill et al., 2010).

Compared to untreated control treatments, solarization treatments were very effective in managing a number of different plant-parasitic nematodes and soilborne diseases on several ornamental crops in Florida (McGovern et al., 2000; 2002; McSorley and McGovern, 2000). However, comparisons of solarization with methyl bromide, rather than against untreated controls, are more critical because fumigation with methyl bromide has been the most effective and standard practice used for managing soilborne pest problems on ornamentals in Florida for many years (Rosskopf et al., 2005). Recent tests suggest that solarization was as effective as methyl bromide in managing weeds in snapdragon (*Antirrhinum majus* L.) crops (McSorley et al., 2004; 2009). Root-knot nematodes (*Meloidogyne* spp.) are considered among the most difficult pests to manage by solarization (Chellemi, 2006; Katan, 1980). It is possible that nematode populations in deeper soil layers can avoid the heating process and then move upward to recolonize solarized soil later in the season. In one recent test, galling from root-knot nematodes was similar in plots treated with methyl bromide or solarization, but yield of snapdragon was greater following methyl bromide (McSorley et al., 2009). In another test, both solarization and methyl bromide were equally effective in managing weeds, but nematode galling and pressure were absent (McSorley et al., 2004). Therefore it is unclear whether solarization can be as effective and consistent as methyl bromide for management of root-knot nematodes. Comparisons of solarization and methyl bromide in sites with significant nematode pressure are crucial, but any such tests must be completed before supplies of methyl bromide diminish to the point where it is not possible to use this material even as a valuable standard of comparison.

The main objective of the current work was to compare the

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performance of solarization with methyl bromide fumigation in sites with pressure from root-knot nematodes, *Meloidogyne incognita* (Kofoid and White) Chitwood. The experimental sites also contained low numbers of stubby-root nematodes, *Paratrichodorus minor* (Colbran) Siddiqi. *Pythium* spp. had occurred previously in one of the sites (McSorley et al., 2009), which was included to provide soilborne disease pressure in addition to root-knot nematodes, in case nematode damage would be more severe in the presence of a disease pathogen. Snapdragon was used as a test crop since it is susceptible to root-knot nematodes and soilborne diseases (McSorley et al., 2009). An additional objective was to determine whether a combination of solarization and drenches of a phosphonate/phosphate product (Biophos®, Eco-Right LLC, Foliar Nutrients Inc., Cairo, GA) would provide improved nematode management and plant performance over solarization alone. Phosphonate compounds have been used against fungal plant pathogens (Cooke and Little, 2002; Opuku et al., 1998; Yandoc et al., 2007; Yandoc-Ables et al., 2007), and related phosphorous compounds were shown to be inhibitory to nematodes (Oka et al., 2007). Recently, Biophos® was tested in the field against root-knot nematodes and showed some potential, although results were inconclusive (McSorley et al., 2009; Thies et al., 2008).

Materials and Methods

Field descriptions. Two experiments were conducted at the University of Florida Plant Science Research and Education Unit (29°24'N, 82°9'W), located near Citra in Marion Co., FL. The soil was Arredondo sand (95% sand, 2% silt, 3% clay), with 1.5% organic matter. Both sites had a history of problems with the root-knot nematode, *M. incognita.* One site (Nematode Site) had been planted with pepper (*Capsicum annuum* L.) during the 2006 and 2007 fall vegetable seasons (McSorley et al., 2008). The other site (Disease Site) was planted with snapdragon during the two previous years, and in addition to root-knot nematodes, had a history of soilborne disease problems caused by *Pythium* spp. (McSorley et al., 2009). This site with *Pythium* spp. was included to have a worst-case scenario, in case damage from a potential complex of root-knot nematodes and soilborne disease was more severe than that resulting from nematodes alone. The management of both sites was similar, and dates of sampling and management activities were the same at both sites. Both fields were treated with glyphosate in early July and then rototilled in late July 2008.

Experimental design and treatments. Each experiment consisted of three treatments in a randomized complete-block design with four replications: solarization, fumigation with methyl bromide, and solarization + Biophos® (20.40% dipotassium phosphonate, 22.67% dipotassium phosphate; Eco-Right LLC, Foliar Nutrients Inc., Cairo, GA). Individual plots were raised beds, 6.1 m long, 20 cm high, and 0.76 m wide at the top, with bed centers spaced 1.8 m apart. Beds were formed on 12 Aug., when the solarization treatments were applied by covering beds with clear, 33-µm-thick, UV-stabilized, low-density polyethylene sheets (Polydak® plastic, Ginegar Plastics Products, Ginegar, Israel). Both solarization treatments (solarization alone, solarization + Biophos®) were treated in an identical manner during the solarization period. The methyl bromide fumigation treatment was applied on 9 Sept. by injecting 560 kg/ha of 50:50 methyl bromide:chloropicrin at a depth of 20 cm through 3 chisels per bed, and immediately covering with opaque, reflective plastic mulch (Sonoco Agricultural Films, Hartsville, SC). The methyl bromide treatment served as the control treatment and standard of comparison with solarization, since fumigation has been the standard practice of growers for many years.

Plastic was removed from all plots in both sites on 30 Sept., when seedlings (2–3 cm tall) of 'Potomac Pink' snapdragon (Speedling Inc., Sun City, FL) were planted. Seedlings were planted in four rows spaced 10 cm apart, with a distance of 10 cm between plants in rows, for a total of 240 plants per plot.

The solarization + Biophos® treatment included four drench applications to the seedlings. The first two applications were applied before planting on 26 Sept. and 30 Sept. by drenching seedlings in a 512-cell tray with 2% Biophos® (10 mL in 500 mL water per tray). This allowed for uptake of the phosphorus compounds before plants were transplanted into the field. The seedlings were then planted into plots that had been solarized. The young plants were drenched in the field on 7 Oct. and 23 Oct. by applying 10 mL Biophos® per plot in 5 L water (45 L Biophos®/ha) by hand with a sprinkling can.

Water and fertilizer were applied through a drip irrigation system. Two irrigation lines were used per bed, with lines placed between the first and second and between the third and fourth rows of plants. Fertilizer was applied initially at a rate of 5.6 kg N/ha per week, increasing to 11.2 kg N/ha in the third week of Oct.

Data collection. Plant heights were measured from five plants per plot on three different dates prior to blooming. On 4 Nov., when wilting was observed in the Disease Site, one plant per plot was removed and samples were sent to the Plant Disease Clinic at the University of Florida, Gainesville, for pathogen identification. Flowers were harvested on 19 Mar., 31 Mar., and 16 Apr. 2009. Opened blooming stems were cut about 3–5 cm above the soil, and total number of cut flower stems were counted, measured, and weighed for each plot.

For evaluation of nematodes, soil samples were collected from all plots on 2 Oct., 11 Feb., and 23 Apr. Four soil cores, 2.5 cm in diameter and 20 cm deep, were collected from each plot and combined into one composite sample. A subsample of 100 cm^3 soil was removed, and nematodes were extracted using a modified sieving and centrifugation method (Jenkins, 1964). Extracted nematodes were then identified and counted under an inverted microscope, and reported as numbers per 100 cm^3 soil. On 28 Apr. at the end of the experiment, five plants were removed from each plot and rated for root galling on a 0–5 scale, where 0 = 0 galls per root system; 1 = 1–2 galls; 2 = 3–10 galls; 3 = 11–30 galls; 4 = 31–100 galls; 5 = >100 galls per root system (Taylor and Sasser, 1978).

Statistical analysis. All data were examined by analysis of variance (ANOVA) using SAS software (version 9.1; SAS Institute, Cary, NC). When ANOVA results were significant ($P < 0.05$), means were separated using the Waller-Duncan K-ratio test.

Results

Nematode site. Numbers of root-knot nematodes (averaging 0.7 nematodes/100 cm^3 soil on 10 Oct. and 6.5 nematodes/100 cm^3 on 11 Feb.) and stubby-root nematodes (1.7 nematodes/100 cm^3 on 10 Oct. and 4.1 nematodes/100 cm^3 on 11 Feb.) in soil samples were relatively low during the growing season and were not affected by the treatments (data not shown). Numbers of both nematodes increased at the end of the snapdragon crop,

Table 1. Effect of preplant soil treatments on nematode numbers and root gall ratings at end of experiments at two sites, 2008–2009.

Treatment	Nematodes per 100 cm³ soil (no.)		Root gall rating
	Stubby-root	Root-knot	
Nematode site			
Methyl bromide:chloropicrin	14.2 a[z]	35.8 a	2.10 b
Solarized	14.2 a	25.3 a	3.00 ab
Solarized + Biophos®	24.5 a	301.5 a	3.45 a
Disease site			
Methyl bromide:chloropicrin	3.8 a	7.2 a	2.45 b
Solarized	4.5 a	8.5 a	3.75 a
Solarized + Biophos®	6.2 a	5.5 a	3.35 a

[z]Data are means of four replications. For each site, means in the same column followed by the same letter are not different ($P \le 0.05$) according to Waller-Duncan K-ratio test.

but remained unaffected by the treatments (Table 1). Distribution of stubby-nematodes was erratic, with high numbers (60 nematodes/100 cm³) in one plot. The methyl bromide:chloropicrin treatment resulted a lower ($P \le 0.05$) level of root galling on the plants than the solarized + Biophos® treatment. On 6 Jan. 2009, the tallest ($P \le 0.10$) plants were observed in plots treated with methyl bromide:chloropicrin (Table 2). However, the treatments did not affect ($P > 0.10$) yields of cut flowers, whether measured in terms of weight or numbers of total cut stems (Table 2). In the methyl bromide:chloropicrin treatment, only 50.5% of the 240 plants were harvested. Harvest rates for the solarized and solarized + Biophos® treatments were 35.1% and 38.1% respectively. The remaining plants were so stunted that no marketable flowers were produced.

Disease site. Numbers of root-knot nematodes during the growing season (1.0 nematodes/100 cm³ on 10 Oct. and 4.1/ nematodes 100 cm³ on 11 Feb.) and initial numbers of stubby-root nematodes (0.2 nematodes/100 cm³) were not affected by treatment (data not shown). However, on 11 Feb., numbers of stubby-root nematodes were greater ($P \le 0.05$) in fumigated plots (4.5 nematodes/100 cm³) than in solarized plots (1.0 nematodes/100 cm³) or solarized + Biophos® plots (1.2 nematodes/100 cm³). Numbers

Table 2. Effect of preplant soil treatments on plant height and yield of harvested snapdragon stems at two sites, 2008–2009.

Treatment	Plant ht (cm)	Wt of cut flowers per plot (g)	Cut stems per plot (no.)
Nematode site			
Methyl bromide:chloropicrin	32.7 a[z]	3469 a	121.2 a
Solarized	30.2 ab	2421 a	84.2 a
Solarized + Biophos®	23.8 b	2268 a	91.5 a
Disease site			
Methyl bromide:chloropicrin	27.0 a	345 a	18.2 a
Solarized	21.2 b	324 a	15.8 a
Solarized + Biophos®	20.6 b	214 a	12.5 a

[z]Data are means of four replications. For each site, means in the same column followed by the same letter are not different ($P \le 0.05$) according to Waller-Duncan K-ratio test. Plant height measured 6 Jan. 2009; harvest data (weight, number) are total of 3 harvests 19 Mar.–16 Apr. 2009. Mean separation at $P \le 0.10$ for plant height at nematode site.

of nematodes in soil did not increase much by the end of the experiment and were not affected by treatments, but root galling was lowest ($P \le 0.05$) following the methyl bromide:chloropicrin treatment (Table 1). Plants were stunted at this site, but the methyl bromide:chloropicrin treatment resulted in the tallest plants (Table 2). Wilted plants were observed as early as 4 Nov., and *Pythium* spp. were recovered from plant samples sent to the Plant Disease Clinic. Despite differences in plant height during the season, no differences in yields were found among treatments (Table 2). Many plants in this site were severely stunted or had died by the end of the season. Only 6.5% of the original plants were harvested across all plots.

Discussion

In general, effects from treatments were similar in both sites. Soil fumigation resulted in reduced root galling and taller plant growth at both sites; however, no improvement in plant yield was obtained. It is interesting that similar levels of galling from root-knot nematodes occurred in both sites. However, final root-knot nematode levels in soil were greater in the Nematode Site than in the Disease Site. Root-knot nematodes were able to invade, develop, and cause galling during the season, but opportunity for reproduction may have been limited by the poor quality and premature death of plants in the Disease Site, resulting in lower numbers in the soil at the end of the season.

Severe pressure from soilborne pest problems occurred at these sites, especially at the Disease Site. The crop was a failure at this site and few plants were harvested despite the soil treatments that were used. Even the standard methyl bromide:chloropicrin fumigation was not beneficial in this site. Although the plant beds were fumigated, we suspect that *Pythium* spp. invaded and recolonized the beds from the unfumigated strips between the rows. In an earlier study that also involved unfumigated row middles, mortality of pepper plants was observed when *Pythium* spp. recolonized beds fumigated with methyl bromide (Saha et al., 2005). The Disease Site was planted to snapdragon during the previous two years and had a history of severe problems with *Pythium* spp. (McSorley et al., 2009). In this third successive year of snapdragon culture, disease pressure had built up in this site to the point where it was difficult to grow a crop, and the untreated areas between rows could be a significant source of pathogen inoculum. Although solarization was not helpful under these conditions, neither was methyl bromide. These results suggest that such severely infested sites should be abandoned or require specific, effective treatment for *Pythium* spp., which was not performed in this study. Possibly non-hosts could be cultivated to break the cycle of severe disease pressure.

In the Nematode Site, yields were highly variable among plots. For example, while solarized plots in several replications yielded <2.0 kg of cut stems per plot, the solarized plot in one replicate yielded 5.4 kg (data not shown). As a result, it was not possible to demonstrate any significant effects of the treatments on cut flower yields, although fumigation enabled early-season plant growth. Methyl bromide was beneficial in reducing root galling on plants but did not affect root-knot nematode levels in soil. Root-knot nematode levels are typically low in soil during the growing season because most of the nematodes are in the roots at that time, so root galling is a more reliable indicator of plant damage. Stubby-root nematodes do not cause root galling and their numbers in soil did not build up as much as root-knot nematodes, so their impact on plant damage was probably minimal. Other authors (Chellemi, 2006; Katan, 1980) have expressed some concern about the difficulty of managing root-knot nematodes with solarization, and the current data on root galling reinforce the idea that solarization is inferior to methyl bromide for this purpose. This problem may be due to the limited length of time during which root-knot nematodes remain suppressed following solarization, because adequate soil heating may not reach deeper soil layers where remnant populations persist. Following summer solarization, root-knot nematodes were suppressed in a fall crop of tomato (*Lycopersicon esculentum* Mill.) in Florida, but recovered and caused galling and damage in the following spring crop (Overman and Jones, 1986). Solarization was capable of suppressing root-knot nematodes for a few months on short-lived ornamental crops (McGovern et al., 2002), but maintaining low levels on a long-lived crop such as snapdragon was not possible in the current study. An interval of 7 months elapsed between the time when the solarization plastic was removed and the end of the snapdragon crop, when root galling was evaluated.

Clearly, longer-term suppression of root-knot nematodes is an important issue to be addressed if solarization is to achieve results comparable to methyl bromide. Some methods suggested for improving solarization include optimizing bed orientation and plastic layers (McGovern et al., 2004), combining solarization with amendments of cabbage or other biofumigants (Gamliel and Stapleton, 1993), or repeating solarization in the same site each year (Candido et al., 2008). Combining solarization with soil steaming or nonfumigant chemicals may be other options for improving performance. However, combining solarization with drenches of Biophos® did not offer any improvement over use of solarization alone in these sites with problems from root-knot nematodes and soilborne disease. Although solarization performed well compared to methyl bromide and other fumigants when nematode pressure was low (McSorley et al., 2004), it was not as effective as methyl bromide in limiting galling from root-knot nematodes or improving early-season plant growth in sites with severe nematode and disease pressure. Adding Biophos® to the solarization treatment did not improve results over solarization alone. Results underscore the need to improve the management of root-knot nematodes by solarization, an important shortcoming of its performance relative to methyl bromide. Although it may be difficult for solarization used alone to exactly match the performance of methyl bromide, which has served as a historic standard for optimum soil pest control, solarization may still be a fairly effective tool if methyl bromide is no longer available.

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