Title
Evaluation of Steam and Soil Solarization for Meloidogyne arenaria Control in Florida Floriculture Crops

Journal
Journal of Nematology, 48(3)

ISSN
0022-300X

Authors
Kokalis-Burelle, Nancy
Rosskopf, Erin N
Butler, David M
et al.

Publication Date
2016

DOI
10.21307/jofnem-2017-026

Journal of Nematology 48(3):183–192. 2016.

Evaluation of Steam and Soil Solarization for *Meloidogyne arenaria* Control in Florida Floriculture Crops

Nancy Kokalis-Burelle,[1] Erin N. Rosskopf,[1] David M. Butler,[2] Steven A. Fennimore,[3] and John Holzinger[4]

Abstract: Steam and soil solarization were investigated for control of the root-knot nematode *Meloidogyne arenaria* in 2 yr of field trials on a commercial flower farm in Florida. The objective was to determine if preplant steam treatments in combination with solarization, or solarization alone effectively controlled nematodes compared to methyl bromide (MeBr). Trials were conducted in a field with naturally occurring populations of *M. arenaria*. Treatments were solarization alone, steam treatment after solarization using standard 7.6-cm-diameter perforated plastic drain tile (steam 1), steam treatment following solarization using custom-drilled plastic drain tile with 1.6-mm holes spaced every 3.8 cm (steam 2), and MeBr applied at 392 kg/ha 80:20 MeBr:chloropicrin. Drain tiles were buried approximately 35 cm deep with four tiles per 1.8 by 30 m plot. Steam application followed a 4-wk solarization period concluding in mid-October. All steam was generated using a Sioux propane boiler system. Plots were steamed for sufficient time to reach the target temperature of 70°C for 20 min. Solarization plastic was retained on the plots during steaming and plots were covered with a single layer of carpet padding to provide additional insulation. The floriculture crops larkspur (*Delphinium elatum* and *Delphinium* × *belladonna*), snapdragon (*Antirrhinum majus*), and sunflower (*Helianthus annuus*) were produced according to standard commercial practices. One month after treatment in both years of the study, soil populations of *M. arenaria* were lower in both steam treatments and in MeBr compared to solarization alone. At the end of the season in both years, galling on larkspur, snapdragon, and sunflowers was lower in both steam treatments than in solarization. Both steam treatments also provided control of *M. arenaria* in soil at the end of the season comparable to, or exceeding that provided by MeBr. Both steam treatments also reduced *M. arenaria* in snapdragon roots comparable to, or exceeding control with MeBr. *Meloidogyne arenaria* in soil increased in solarization alone. Solarization alone also had higher gall ratings on larkspur, snapdragon, and sunflower than all other treatments. Steam provided excellent control of *M. arenaria* in this study.

Key words: Antirrhinum majus, *Delphinium* × *belladonna*, *Delphinium elatum*, fumigation, *Helianthus annuus*, methyl bromide alternatives, root-knot nematodes.

Producers of inground floriculture crops continue to search for effective and affordable means to control soilborne pests including nematodes. Due to the diversity of crops grown and the flexibility in planting dates required for reaching specific marketing windows with specific crops, the use of MeBr was a key tool in the production of these high-value commodities. The loss of MeBr has left a significant gap in soilborne pest control that has not been filled with alternative fumigants. Propane-fueled steam is being researched and developed as a potentially viable method for treating production fields for pest control. The majority of research on steam for soilborne pest control conducted in the United States has been in California and Florida, but a great deal of research has also been conducted in European countries including Italy and Spain. Most research on steam for pest control has been conducted on high-value ornamental and vegetable/fruit crops including cut flowers (Rainbolt et al., 2013), tomatoes (Luvisi et al., 2008), strawberries (Samtani et al., 2012; Fennimore et al., 2014), and other crops (Triolo et al., 2004) produced in either flat field plots or raised beds. Steam has been demonstrated to produce temperatures in soil high enough to control soilborne pests including nematodes (Van Loenen et al., 2003), soilborne fungal pathogens (Van Loenen et al., 2003; Triolo et al., 2004; Luvisi et al., 2008), and weeds (Van Loenen et al., 2003; Melander and Jorgensen, 2005; Raffaelli et al., 2016). Challenges for steam application include adequate heating of soil, consistency of heat transfer rates in different soil types, variability in water content of soil, and cost effectiveness of treatments.

Combining steam with other soil treatments such as soil solarization has shown potential to address some of these challenges (Rainbolt et al., 2013). Soil solarization is the passive heating of soil covered with a plastic mulch which, in many areas of the United States, has proven inadequate for parasitic nematode control on its own (Zasada et al., 2010). In turn, combining soil solarization with other techniques including organic soil amendments to improve nematode control over solarization alone has been proposed (Stapleton, 2000). In practice, however, combining solarization with broccoli residue did not improve parasitic nematode control over application of the broccoli amendment without solarization (Zasada et al., 2003). Gamliel et al. (2000) combined solarization with soil fumigants to achieve control of soilborne pathogens.

Steam has also been combined with other techniques including use of KOH or CaO (Bárberi et al., 2009; Meszka and Malusà, 2014) for soilborne pathogen and weed control. In studies on the effects of steam combined with KOH and CaO as activating compounds on weed suppression, there were no effects of steam on

Received for publication May 27, 2016.
[1]USDA, ARS, U.S. Horticultural Research Lab, 2001 South Rock Road, Fort Pierce, FL 34945.
[2]University of Tennessee, Knoxville, TN 37996.
[3]University of California, Davis, CA 95616.
[4]Holzinger Flowers, Inc., Palm City, FL 34990.
We would like to acknowledge Kate Rotindo, Jackie Markle, Melissa Edgerly, Veronica Abel, and Shardy Sauveur for their technical assistance.
We wish to acknowledge funding from USDA-NIFA, Methyl Bromide Transitions Program (2207-02951) and the Propane Education and Research Council (PERC).

E-mail: nancy.burelle@ars.usda.gov.
This paper was edited by Andrea M. Skantar.

FIG. 1. Perforated medium density polyethylene plastic pipe (7.6 cm diameter) used with saturated steam. This method is well suited for combined use with solarization, and is relatively efficient with regard to fuel consumption. Four pipes were installed in each planting bed, with at least one pipe per foot of bed width. Pipes were laid in trenches at 35-cm depth with the objective of heating the top 20 cm of soil. Lower right: standard 7.6 cm perforated plastic drain tile (steam 1), lower left: custom-drilled plastic drain tile with 1.6-mm holes spaced every 3.8 cm (steam 2).

total weed density, but there were effects on individual weed species. It was determined that the type and rates of activating compounds for soil steaming must be adjusted to the weed community composition (Bárberi et al., 2009). Steam application combined with mustard seed meal as a soil amendment was also shown to enhance weed and pathogen control in California strawberry production (Fennimore et al., 2014).

Literature on the direct effects of steaming field soil on plant-parasitic nematodes is limited. However, in a study investigating the indirect effects of steam on soil microflora and nematode populations, McSorley et al. (2006) reported that populations of the root-knot nematode *Meloidogyne incognita* were suppressed when inoculated into a nonsteamed sandy soil, but were not suppressed when added into a steamed sandy soil. This effect was attributed to a reduction in predatory nematodes by the steam treatment. In studies demonstrating the direct effect of steam on root-knot nematodes and weed populations in soil, Rosskopf et al. (2010) found that, in addition to reduced galling by root-knot nematodes in several floriculture crops, steam treatments were comparable to MeBr in reducing weed biomass compared with solarization alone.

In the current study, propane-fueled steam was investigated for efficacy in controlling root-knot nematodes as an alternative to chemical fumigants under Florida production conditions. Field trials were conducted in Florida to evaluate saturated steam applied through buried polyethylene pipes following soil solarization for nematode control in several cut flower crops. The objective of the research was to determine if preplant steam treatments combined with soil solarization could effectively control the root-knot nematode

FIG. 2. Sioux propane steam generator provides 383 kg/hr of saturated steam at 5 to 10 psig.

M. arenaria in floriculture crops in a commercial production field. Experimental treatments were compared to a MeBr standard commercial treatment.

MATERIALS AND METHODS

Experimental design

A field trial was established on a commercial flower production farm in Palm City, FL. Treatments were arranged in a randomized complete block design with four replications. Treatments were solarization alone (1.3-mil Polydak, UV-stabilized transparent film, Ginegar Plastics, Israel), steam treatment after solarization using standard 7.6-cm-diameter perforated polyethylene plastic pipe (Hancor, Findlay, OH) (steam 1), steam treatment following solarization using custom-drilled polyethylene plastic pipe with 1.6-mm holes spaced every 3.8 cm (steam 2) (Fig. 1), and MeBr applied at 392 kg/ha 80:20 MeBr:chlorpicrin. Steam pipes were buried approximately 35 cm deep with four pipes per 1.8 by 30 m plot. Steam application followed a 4-wk solarization period concluding in mid-October. All steam was generated using the Sioux portable propane boiler system (Sioux Corporation, Beresford, SD) (Fig. 2), which provided 383 kg/hr of saturated steam at 5 to 10 psig. Plots were steamed for sufficient time to reach the target temperature of 70°C for 20 min. Soil temperatures were monitored with soil temperature probes. Solarization plastic was retained on the plots during steaming and plots were covered with a single layer of carpet padding to provide insulation and increase heat retention. Plastic was removed prior to planting.

Nematode and disease assessments

Before steam application pipes and solarization plastic were installed, soil samples were collected from each plot and analyzed for baseline nematode populations. At the completion of the

TABLE 1. Soil nematode populations from pre- and poststeam treatment in year 1.

	M. arenaria J_2/ 100 cm^3 soil	Nonparasitic No./ 100 cm^3 soil	*M. arenaria* J_2/ 100 cm^3 soil	Nonparasitic No./ 100 cm^3 soil
	Presteam treatment 9-3-09		Poststeam treatment 10-22-09	
Methyl bromide	8.51 a[a]	204.12 a	0.00 b	130.41 a
Solarization	0.00 a	158.76 a	5.67 a	103.48 a
Steam 1[b]	0.00 a	124.74 a	0.00 b	24.81 b
Steam 2	31.19 a	204.12 a	0.00 b	15.81 b
LSD (0.05)	34.34	226.12	2.82	55.87

LSD = least significant difference; *M. arenaria* = *Meloidogyne arenaria*.
[a] Means with the same letter within a column are not significantly different at $P \leq 0.05$.
[b] Steam 1 accomplished using standard 7.6-cm-diameter perforated polyethylene plastic pipe; steam 2 accomplished using custom-drilled polyethylene plastic pipe with 1.6-mm holes spaced every 3.8 cm.

steam application, soil sampling was repeated. Samples were collected at 0 to 12 cm depth between steam pipes. Ten to fifteen soil cores were taken in each plot using a 1.75-cm internal diameter soil probe and combined. A 100-cm^3 subsample of soil was used for nematode extraction. Nematode populations in soil were assessed immediately before soil treatment, 2 wk after treatment, and at the end of the harvest period for each crop.

Data on root nematode populations, gall ratings, and plant growth were collected from two plant samples within each plot at the end of the season for all crops (see below). Nematodes were extracted from both soil and roots using the Baermann funnel technique and *Meloidogyne* spp. and free-living (microbivorous and predatory) nematodes were identified after samples were in funnels for 2 d. Roots were evaluated for galling, root necrosis (root condition ratings), and plant growth including shoot and root weight. Root condition was used as a general indicator of root necrosis and was assessed using a subjective scale of 0 to 5 with 0 to 1.0 = 0% to 20% discolored roots, 1.0 to 2.0 = 21% to 40%, 2.0 to 3.0 = 41% to 60%, 3.0 to 4.0 = 61% to 80%, and 4.0 to 5.0 = 81% to 100%. Root galling was assessed using a root gall index based on a scale of 0 to 10, with 0 representing no galls and 10 representing severe (100%) galling (Bridge and Page, 1980). Gravid females were extracted from roots and identified based on enzyme phenotypes as *M. arenaria* using the Phast system (GE Healthcare Bio-Sciences Corp., Piscataway, NJ) (Esbenshade and Triantaphyllou, 1985, 1990).

Due to the market and production requirements of the grower, the field was divided into three subsections and planted to three different crops each year, which were selected based on the duration of the crop. In year 1, snapdragon (*A. majus*), larkspur (*D. elatum*), and delphinium (*Delphinium* × *belladonna*) were evaluated. Mid- and lateseason soil samplings were performed for snapdragon and larkspur, with only lateseason samples collected for delphinium due to production constraints. Analysis of soil nematodes and root necrosis was conducted as previously described. In addition, yield of marketable stems was recorded by the grower cooperator for snapdragon and larkspur. Due to lack of market demand, the delphinium crop was not harvested. In year 2, pretreatment, poststeam treatment, and postsolarization treatment samples were collected as in year 1 as previously described. Sunflowers were grown in year 2 in place of larkspur due to market demand. Snapdragon and delphinium were both produced in year 2, repeating year 1 trials. Soil and roots were assessed for all crops as described for year 1.

Statistical analysis

Data were statistically analyzed according to standard procedures including SAS analysis of variance and least significant difference (SAS Institute, Cary, NC). Unless otherwise stated, all differences referred to in the text were significant at the 5% level of probability.

TABLE 2. Soil and root nematode populations from mid- and lateseason snapdragon (*Antirrhinum majus*), plant growth, root galling, and root condition at the end of the season in year 1.

	M. arenaria J_2/100 cm^3 soil	Nonparasitic No./100 cm^3 soil	*M. arenaria* J_2/100 cm^3 soil	Nonparasitic No./100 cm^3 soil	*M. arenaria* J_2/g root	Nonparasitic No./g root	Root condition[a]	Gall index[b]	Stem diameter (mm)	Root weight (g)	Shoot weight (g)	Height (cm)
	Midseason nematodes		End-of-season nematodes				End-of-season plant ratings					
Methyl bromide	5.67 a[c]	890.20 a	72.29 a	2,277.90 ab	12.50 b	26.64 a	0.68 c	2.08 b	7.04 a	4.73 b	24.80 b	59.58 c
Solarization	14.18 a	662.70 a	15.59 b	1,020.60 c	49.81 a	33.82 a	0.70 c	3.15 a	6.80 a	6.56 a	28.52 ab	59.98 bc
Steam 1[d]	0.00 a	829.90 a	2.84 b	1,927.80 bc	1.93 b	18.21 a	1.13 b	0.27 c	7.00 a	4.92 b	31.03 a	64.77 ab
Steam 2	0.00 a	997.90 a	0.00 b	3,044.80 a	0.28 b	16.08 a	1.77 a	0.11 c	6.63 a	4.92 b	28.31 ab	67.02 a
LSD (0.05)	15.49	410.47	46.97	1,003.40	20.62	18.32	0.34	0.95	0.56	1.20	4.10	4.94

LSD = least significant difference; *M. arenaria* = *Meloidogyne arenaria*.
[a] Root condition is as follows: 0 = clean, white roots, 5 = totally rotted, discolored roots.
[b] Gall index is as follows: 0 = no galling, 10 = total galling.
[c] Means with the same letter within a column are not significantly different at $P \leq 0.05$.
[d] Steam 1 accomplished using standard 7.6-cm-diameter perforated polyethylene plastic pipe; steam 2 accomplished using custom-drilled polyethylene plastic pipe with 1.6-mm holes spaced every 3.8 cm.

Results

Pretreatment number of *M. arenaria* in soil was low or 0 (per 100 cm^3) in all treatment areas (Table 1). Those numbers were reduced to 0 following all treatments except solarization, which saw in increase in numbers of *M. arenaria* J_2 in soil following treatment. Numbers of nonparasitic nematodes in soil before treatment were high and evenly distributed across the test area. Nonparasitic nematodes in soil were significantly reduced in both steam treatments compared with MeBr and solarization 7 wk after treatment application (Table 1).

In snapdragon, midseason nematode populations in soil did not differ among treatments (Table 2). However, by the end of the season, *M. arenaria* J_2 in soil were higher in the MeBr treatment than all other treatments, and populations in snapdragon roots were higher in the solarization treatment than in all other treatments (Table 2). At the end of the season, root condition ratings for snapdragon were better in the MeBr and solarization treatments. However, galling by root-knot nematodes was significantly reduced in both steam treatments compared to MeBr and solarization. Root weight was highest in the solarization treatment, most likely due to the high level of galling (Table 2). In floriculture crops, shoot weight and height are often better indicators of treatment efficacy than root weight, which is often higher in heavily galled plants. Steam 1 had higher shoot weights than MeBr, and steam 2 had higher shoot heights than both MeBr and solarization (Table 2). Nonparasitic nematode populations in soil were similar in all treatments at midseason, and highest in soil in the steam 2 treatment at the end of the season (Table 2). There were no differences in nonparasitic nematode numbers in roots at the end of the season.

In larkspur plots, all treatments eliminated *M. arenaria* J_2 in soil at midseason and populations remained low in soil in all treatments until the end of the season (Table 3). However, in larkspur roots at the end of the season, MeBr and steam 2 had significantly lower *M. arenaria* J_2 in roots than solarization and steam 1, whereas steam 1 had higher populations of nonparasitic nematodes in roots than MeBr (Table 3). Populations of nonparasitic nematodes in soil were highest in the solarization treatment at midseason but were lower than MeBr by the end of the season. Steam 1 had higher numbers of nonparasitic nematodes in roots than MeBr. There were no differences among soil treatments in larkspur root condition ratings at the end of the season (Table 3). However, galling was significantly lower in the steam 2 treatment than in both the MeBr and solarization treatments. Solarization also generally had lower plant growth ratings than other treatments including stem diameter, root weight, shoot weight, and plant height (Table 3).

Meloidogyne arenaria populations were collected from delphinium plots only one time, which was at the end of

Table 3. Soil and root nematode populations from mid- and lateseason larkspur (*Delphinium elatum*), plant growth, root galling, and root condition at the end of the season in year 1.

	Midseason nematodes		End-of-season nematodes				End-of-season plant ratings					
	M. arenaria J_2/ 100 cm^3 soil	Nonparasitic No./ 100 cm^3 soil	*M. arenaria* J_2/ 100 cm^3 soil	Nonparasitic No./ 100 cm^3 soil	*M. arenaria* J_2/g root	Nonparasitic No./g root	Root condition[a]	Gall index[b]	Stem diameter (mm)	Root weight (g)	Shoot weight (g)	Height (cm)
Methyl bromide	0.00 a[c]	577.6 ab	9.92 a	1,231.80 a	0.00 b	98.40 b	0.76 a	2.14 a	7.18 a	4.05 a	28.15 a	70.69 a
Solarization	0.00 a	747.0 a	0.00 a	463.50 b	7.38 a	147.01 ab	1.06 a	1.78 ab	6.51 b	3.08 b	22.70 b	65.88 b
Steam 1[d]	0.00 a	639.6 ab	8.51 a	1,122.70 ab	6.95 a	184.42 a	0.99 a	0.84 bc	7.16 a	4.32 a	26.75 ab	66.31 b
Steam 2	0.00 a	428.1 b	3.24 a	837.50 ab	0.13 b	117.87 ab	0.88 a	0.70 c	7.07 a	3.70 ab	24.00 ab	66.50 b
LSD (0.05)	0.00	314.7	11.91	734.58	5.60	84.60	0.63	0.94	0.50	0.69	4.21	3.73

LSD = least significant difference; *M. arenaria* = *Meloidogyne arenaria*.
[a] Root condition is as follows: 0 = clean, white roots, 5 = totally rotted, discolored roots.
[b] Gall index is as follows: 0 = no galling, 10 = total galling.
[c] Means with the same letter within a column are not significantly different at $P \leq 0.05$.
[d] Steam 1 accomplished using standard 7.6-cm-diameter perforated polyethylene plastic pipe; steam 2 accomplished using custom-drilled polyethylene plastic pipe with 1.6-mm holes spaced every 3.8 cm.

TABLE 4. Soil and root nematode populations from late-season delphinium (*Delphinium* × *belladonna*), plant growth, root galling, and root condition at the end of the season in year 1.

	M. arenaria J_2/ 100 cm^3 soil	Nonparasitic No./ 100 cm^3 soil	*M. arenaria* J_2/g root	Nonparasitic No./g root	Root condition[a]	Gall index[b]	Stem diameter (mm)	Root weight (g)	Shoot weight (g)
	End–of-season nematodes				End-of-season plant ratings				
Methyl bromide	1.42 a[c]	653.5 a	1.31 a	60.58 a	1.38 a	0.04 a	7.76 a	5.12 b	19.96 a
Solarization	0.00 a	572.7 ab	0.35 a	39.17 a	1.50 a	0.02 a	8.06 a	6.14 ab	15.75 b
Steam 1[d]	0.00 a	395.5 ab	0.35 a	67.82 a	1.89 a	0.03 a	7.93 a	6.62 a	18.09 ab
Steam 2	0.00 a	258.0 b	0.00 a	65.78 a	1.82 a	0.02 a	7.57 a	5.44 ab	14.48 b
LSD (0.05)	2.06	389.2	1.463	33.87	0.53	0.04	1.00	1.38	4.15

LSD = least significant difference; *M. arenaria* = *Meloidogyne arenaria*.
[a] Root condition is as follows: 0= clean, white roots, 5 = totally rotted, discolored roots.
[b] Gall index is as follows: 0 = no galling, 10 = total galling.
[c] Means with the same letter within a column are not significantly different at $P \leq 0.05$.
[d] Steam 1 accomplished using standard 7.6-cm-diameter perforated polyethylene plastic pipe; steam 2 accomplished using custom-drilled polyethylene plastic pipe with 1.6-mm holes spaced every 3.8 cm.

the season. Nematode populations in soil and roots of delphinium at that time were very low, and did not differ among treatments, with the exception of lower numbers of nonparasitic nematodes in soil in the steam 2 treatment compared with MeBr (Table 4). Root condition and gall index values were also very low and did not differ among treatments indicating that the delphinium hybrid used in these trials was not susceptible to *M. arenaria* (Table 4). Stem diameter also did not differ among treatments but root weight and shoot weight were highest in the steam 1 treatment (Table 4). These results are consistent with previous research on this delphinium hybrid variety (Kokalis-Burelle and Rosskopf, 2013).

In the second year of the study, pretreatment soil populations of *M. arenaria* and nonparasitic nematodes were evenly distributed among plots (Table 5). Following the steam and solarization treatment application, both steam treatments eliminated *M. arenaria* from soil, whereas solarization did not (Table 5). Nonparasitic nematodes in soil did not differ among plots before steam application but following steam application both steam treatments, and the solarization treatment, had fewer nonparasitic nematodes than MeBr (Table 5).

Sunflowers were substituted for larkspur in the second year of the trial at the grower's discretion based on marketability of the crops at the time. At mid- and lateseason, all soil treatments controlled *M. arenaria* populations in soil. Both steam treatments also reduced nonparasitic nematodes early in the season compared to MeBr and solarization (Table 6). However, by the end of the season, nonparasitic nematodes had rebounded in the steam treatment and were higher in soil than the solarization treatment. Isolation of *M. arenaria* J_2 from sunflower roots increased in the solarization treatment compared with both steam treatments at the end of the season (Table 6). Nonparasitic nematodes in roots were higher in steam 1 than in MeBr or steam 2 (Table 6). Stem diameter of sunflower was lowest in both steam treatments and stem height was lowest in steam 2 (Table 6). Shoot weight and root weight did not differ among treatments. Root condition and gall ratings on sunflower were significantly higher in the solarization treatment compared with all other treatments. Both steam treatments were comparable to MeBr for root condition and gall index values (Table 6).

Results of the second season of snapdragon trials showed midseason *M. arenaria* populations in soil to be low and not significantly different among soil treatments (Table 7). There were greater differences among nonparasitic nematodes at the early season sampling time with the steam 2 treatment having the highest number and solarization having the lowest number of nonparasitic nematodes (Table 7). At the end of the snapdragon season, there were no differences among

TABLE 5. Soil nematode populations from pre- and poststeam treatments in year 2.

	M. arenaria J_2/100 cm^3 soil	Nonparasitic No./100 cm^3 soil	*M. arenaria* J_2/100 cm^3 soil	Nonparasitic No./100 cm^3 soil
	Presteam treatment		Poststeam treatment	
Methyl bromide	2.84 a[a]	212.63 a	2.84 ab	507.47 a
Solarization	0.00 a	189.95 a	5.67 a	202.70 b
Steam 1[b]	5.67 a	246.65 a	0.00 b	24.10 b
Steam 2	2.84 a	181.44 a	0.00 b	26.93 b
LSD (0.05)	10.47	120.71	4.73	186.38

LSD = least significant difference; *M. arenaria* = *Meloidogyne arenaria*.
[a] Means with the same letter within a column are not significantly different at $P \leq 0.05$.
[b] Steam 1 accomplished using standard 7.6-cm-diameter perforated polyethylene plastic pipe; steam 2 accomplished using custom-drilled polyethylene plastic pipe with 1.6-mm holes spaced every 3.8 cm.

Table 6. Soil and root nematode populations from mid- and lateseason sunflower (*Helianthus annuus*), plant growth, root galling, and root condition at the end of the season in year 2.

	M. arenaria J_2/ 100 cm^3 soil	Nonparasitic No./ 100 cm^3 soil	*M. arenaria* J_2/ 100 cm^3 soil	Nonparasitic No./ 100 cm^3 soil	*M. arenaria* J_2/g root	Nonparasitic No./g root	Root condition[a]	Gall index[b]	Stem diameter (mm)	Root weight (g)	Shoot weight (g)	Height (cm)
	Midseason nematodes		End-of-season nematodes				End-of-season plant ratings					
Methyl bromide	0.00 a[c]	470.61 a	0.00 a	304.8 ab	0.64 ab	7.97 b	0.65 b	0.09 b	9.85 a	11.30 a	111.93 a	81.34 a
Solarization	0.00 a	333.11 a	0.00 a	123.3 b	2.96 a	19.57 ab	1.16 a	0.51 a	10.08 a	10.30 a	100.84 a	76.88 ab
Steam 1[d]	0.00 a	134.66 b	0.00 a	501.8 a	0.02 b	27.05 a	0.80 b	0.01 b	8.89 b	11.21 a	91.13 a	75.16 ab
Steam 2	0.00 a	131.83 b	0.00 a	452.2 a	0.30 b	13.75 b	0.78 b	0.15 b	8.75 b	13.20 a	91.03 a	72.94 b
LSD (0.05)	0.00	146.6	0.00	234.38	2.58	12.05	0.24	0.23	0.85	3.32	24.82	6.67

LSD = least significant difference; *M. arenaria* = *Meloidogyne arenaria*.

[a] Root condition on a 0 to 5 scale with 0 = no root discoloration and 5 = total root discoloration.

[b] Gall index is as follows: 0 = no galling, 10 = total galling.

[c] Means with the same letter within a column are not significantly different at $P \leq 0.05$.

[d] Steam 1 accomplished using standard 7.6-cm-diameter perforated polyethylene plastic pipe; steam 2 accomplished using custom-drilled polyethylene plastic pipe with 1.6-mm holes spaced every 3.8 cm.

treatments for soil populations of *M. arenaria* or nonparasitic nematodes (Table 7). However, *M. arenaria* and nonparasitic nematodes isolated from roots were significantly higher in the solarization treatment compared with all other treatments. Solarization also had lower plant growth and higher gall index values than all other soil treatments (Table 7). MeBr had the lowest root condition ratings of all treatments (Table 7).

Results of the second year of delphinium production were consistent with those from the first year, with very low numbers of *M. arenaria* J_2 in soil in all treatments early in the season (Table 8) and in soil and roots at the end of the season (Table 8). Nonparasitic nematodes in soil did not differ among treatments early in the season but did increase late in the season in the steam 2 treatment, which had significantly more nonparasitic nematodes compared with solarization (Table 8). There were also no significant effects of treatments on root condition, gall index values, stem diameter, root weight, or shoot weight of delphinium at the end of the season (Table 8). Plant height values were higher in steam 2 compared with solarization (Table 8).

Discussion

Results from the commercial floriculture field trials presented here demonstrated that steaming soil in the field following a soil solarization period was more efficacious for root-knot nematode control than soil solarization alone, and was comparable to the nematode control achieved with MeBr fumigation. Growers have been attempting to effectively apply soil solarization for nematode and weed control in Florida for years with only limited success (Martin, 2003; Rosskopf et al., 2005). This lack of success has been primarily attributed to the high levels of nematode inoculum in the deep, sandy soils found in Florida, which solarization does not reach (Noling, 2015). The long production season of many floriculture crops, as well as repeated plantings after one soil treatment, requires that nematode control measures remain effective for an extended period for floriculture crops compared with shorter season vegetable crops. In previous multi-year research on soil fumigants conducted at this farm, population levels of *M. arenaria* in field trials using methyl iodide and MeBr were controlled early in the season but would typically rebound by harvest to levels equal to or higher than the nontreated control plots (Kokalis-Burelle et al., 2010). This phenomenon is an indication of the unsustainable nature of controlling plant-parasitic nematodes with chemical soil fumigation and has been observed repeatedly in subsequent trials.

The application of steam for nematode and other soilborne pest control continues to be evaluated and refined in both Florida and California. From the data collected in this trial, it cannot be determined if steam application without solarization would be equally

Table 7. Soil and root nematode populations from mid- and lateseason snapdragon (*Antirrhinum majus*), plant growth, root galling, and root condition at the end of the season in year 2.

	M. arenaria J_2/100 cm^3 soil	Nonparasitic No./100 cm^3 soil	*M. arenaria* J_2/100 cm^3 soil	Nonparasitic No./100 cm^3 soil	*M. arenaria* J_2/g root	Nonparasitic No./g root	Root condition[a]	Gall index[b]	Stem diameter (mm)	Root weight (g)	Shoot weight (g)	Height (cm)
	Midseason nematodes		End-of-season nematodes				End-of-season plant ratings					
Methyl bromide	0.00 a[c]	789.5 ab	0.00 a	684.7 a	1.07 b	19.22 b	0.81 b	1.20 b	7.54 a	5.42 b	50.92 a	23.88 a
Solarization	7.09 a	279.2 c	1.42 a	574.1 a	34.33 a	69.68 a	1.74 a	2.39 a	6.19 b	4.34 c	32.61 b	17.12 b
Steam 1[d]	2.84 a	552.8 bc	0.00 a	657.7 a	2.34 b	16.98 b	1.60 a	1.06 bc	7.74 a	6.53 a	47.25 a	23.59 a
Steam 2	0.00 a	962.5 a	0.00 a	657.7 a	0.52 b	14.37 b	1.48 a	0.68 c	7.78 a	5.69 b	49.92 a	22.78 a
LSD (0.05)	7.12	323.95	2.06	545.44	19.87	34.30	0.46	0.47	1.14	0.76	8.57	1.21

LSD = least significant difference; *M. arenaria* = *Meloidogyne arenaria*.
[a] Root condition on a 0 to 5 scale with 0 = no root discoloration and 5 = total root discoloration.
[b] Gall index is as follows: 0 = no galling, 10 = total galling.
[c] Means with the same letter within a column are not significantly different at $P \leq 0.05$.
[d] Steam 1 accomplished using standard 7.6-cm-diameter perforated polyethylene plastic pipe; steam 2 accomplished using custom-drilled polyethylene plastic pipe with 1.6-mm holes spaced every 3.8 cm.

effective, but it is clear that solarization alone did not provide adequate nematode control. In other trials conducted comparing solarization and steam alone, and combined, there was no benefit to combining steam with solarization, except for the limited control of the hard-seeded weed *Malva parviflora* using blanket-applied steam combined with solarization (Samtani et al., 2012; Rainbolt et al., 2013). However, injection of steam below the soil surface produced the best results in terms of weed and pathogen control (Rainbolt et al., 2013).

Effects of treatments on nonparasitic nematodes have been used as indicators of the impact of treatments on soil microbial populations. Previous studies have demonstrated that steaming soil resulted in lower abundance of free-living nematodes initially, but populations rebounded and were more abundant in steamed soil compared with nonsteamed soil at the end of experiments (McSorley et al., 2006). In the studies presented here, nonparasitic nematodes were equivalent prior to treatment. Following treatment, they were reduced in steam to a greater degree than MeBr in both years. Nonparasitic nematode numbers in soil and roots rebounded more quickly following all treatments than did the *M. arenaria* population throughout the season. Steam treatments initially reduced nonparasitic soil nematode populations to a greater degree than solarization, which may be due to the deeper effect of steaming soil on both nematode and soil microbial populations compared with the more shallow effect of soil solarization.

The use of buried drain tile is a common practice for Florida specialty crop producers, with semipermanent drain tile systems installed at 60 cm (Boman and Tucker, 2002). Therefore, growers are familiar with the installation of tiles for drainage. On the basis of our research experience, when tiles are used for steaming beds they can remain in place for 5 or more years. From the results presented here, the custom-drilled tile (steam 2) provided more consistent control of root-knot nematodes. However, the custom-drilled drain tiles are not currently commercially available, and growers would need to weigh the cost of production of the tiles against any enhancement in nematode control.

In the studies presented here, steaming was more effective than solarization, and was comparable to MeBr fumigation for root-knot nematode control and yield enhancement in cut flower production. However, the negative impact of steam on nontarget free-living nematodes, and on root condition are aspects of steaming soil that need to be considered. In addition, delphinium did not benefit from steaming soil for root-knot nematode control, and thus farmers should not invest in this treatment for nematode control when growing delphinium in nematode-infested fields. Floriculture producers who have observed the success of steam for nematode control have expressed interest in using the buried pipe method, particularly for treating areas with permanent structures such as inside, and adjacent to shade houses. The primary challenges that remain for successful U.S. market adoption are the optimization of mobile steam generation techniques suitable for U.S. fields, and optimization of compatible steam application technologies with flexibility that serves preplant applications.

TABLE 8. Soil and root nematode populations from mid- and lateseason in delphinium (*Delphinium* × *belladonna*), plant growth, root galling, and root condition at the end of the season in year 2.

	Midseason nematodes		End-of-season nematodes						End-of-season plant ratings			
	M. arenaria J_2/ 100 cm^3 soil	Nonparasitic No./ 100 cm^3 soil	*M. arenaria* J_2/ 100 cm^3 soil	Nonparasitic No./ 100 cm^3 soil	*M. arenaria* J_2/g root	Nonparasitic No./g root	Root condition[a]	Gall index[b]	Stem diameter (mm)	Root weight (g)	Shoot weight (g)	Height (cm)
Methyl bromide	0.00 a[c]	148.84 a	0.00 a	223.97 ab	0.06 b	29.99 a	1.16 a	0.02 a	8.45 a	6.65 a	30.15 a	70.56 ab
Solarization	1.42 a	171.52 a	0.00 a	134.66 b	0.65 a	18.83 a	1.48 a	0.08 a	7.08 a	8.51 a	30.18 a	65.21 b
Steam 1[d]	0.00 a	124.74 a	0.00 a	153.09 ab	0.04 b	18.21 a	1.11 a	0.01 a	7.52 a	8.95 a	32.45 a	71.88 ab
Steam 2	0.00 a	188.53 a	0.00 a	256.57 a	0.00 b	29.86 a	0.96 a	0.00 a	8.17 a	7.23 a	36.75 a	77.21 a
LSD (0.05)	2.06	89.97	0.00	112.76	0.54	25.04	0.54	0.09	2.03	2.46	8.25	8.26

LSD = least significant difference; *M. arenaria* = *Meloidogyne arenaria*.
[a] Root condition on a 0 to 5 scale with 0 = no root discoloration and 5 = total root discoloration.
[b] Gall index is as follows: 0 = no galling, 10 = total galling.
[c] Means with the same letter within a column are not significantly different at $P \leq 0.05$.
[d] Steam 1 accomplished using standard 7.6-cm-diameter perforated polyethylene plastic pipe; steam 2 accomplished using custom-drilled polyethylene plastic pipe with 1.6-mm holes spaced every 3.8 cm.

Literature Cited

Bárberi, P., Moonen, A. C., Peruzzi, A., Fontanelli, M., and Raffaelli, M. 2009. Weed suppression by soil steaming in combination with activating compounds. Weed Research 49(1):55–66.

Boman, B. J., and Tucker, D. 2002. Drainage systems for flatwoods citrus in Florida. University of Florida, EDIS publication, Circular no. 1412.

Bridge, J., and Page, S. L. J. 1980. Estimation of root-knot infestation levels in roots using a rating chart. Tropical Pest Management 26:296–298.

Esbenshade, P. R., and Triantaphyllou, A. C. 1985. Use of phenotypes for identification of *Meloidogyne* species. Journal of Nematology 17(1):6–20.

Esbenshade, P. R., and Triantaphyllou, A. C. 1990. Isozyme phenotypes for the identification of *Meloidogyne* species. Journal of Nematology 22(1):10–15.

Fennimore, S. A., Martin, F. N., Miller, T. C., Broome, J. C., Dorn, N., and Greene, I. 2014. Evaluation of a mobile steam applicator for soil disinfestation in California strawberry. HortScience 49(12):1542–1549.

Gamliel, A., Grinstein, A., Zilberg, V., Beniches, M., Katan, J., and Ucko, O. 2000. Control of soilborne diseases by combining soil solarization and fumigants. Acta Horticulturae 532:157–164.

Kokalis-Burelle, N., and Rosskopf, E. N. 2013. Susceptibility of several floriculture crops to three common species of *Meloidogyne* in Florida. Nematropica 43:164–170.

Kokalis-Burelle, N., Rosskopf, E. N., Albano, J. P., and Holzinger, J. 2010. Effects of Midas® on nematodes in commercial floriculture production in Florida. Journal of Nematology 42(1):17–21.

Luvisi, A., Materazzi, A., and Triolo, E. 2008. Control of soil-borne diseases in tomato by use of steam and an exothermic reaction. Advances in Horticultural Science 22(3):174–181.

Martin, F. N. 2003. Development of alternative strategies for management of soilborne pathogens currently controlled with methyl bromide. Annual Review of Phytopathology 41:325–350.

McSorley, R., Wang, K.-H., Kokalis-Burelle, N., and Church, G. 2006. Effects of soil type and steam on nematode biological control potential of the rhizosphere community. Nematropica 36(2):197–214.

Melander, B., and Jorgensen, M. H. 2005. Soil steaming to reduce intrarow weed seedling emergence. Weed Research 45(3):202–211.

Meszka, B., and Malusà, E. 2014. Effects of soil disinfection on health status, growth and yield of strawberry stock plants. Crop Protection 63:113–119.

Noling, J. 2015. New insights relating the spatial distribution and management of nematodes in Florida soils. Journal of Nematology 47 (3):260.

Raffaelli, M., Martelloni, L., Frasconi, C., Fontanelli, M., Carlesi, S., and Peruzzi, A. 2016. A prototype band-steaming machine: Design and field application. Biosystems Engineering 144:61–71.

Rainbolt, C. M., Samtani, J. B., Fennimore, S. A., Gilbert, C. A., Subbaro, K. V., Gerik, J. S., Shrestha, A. A., and Hanson, B. D. 2013. Steam as a preplant soil disinfestation tool in California cut-flower production. HortTechnology 23(2):207–214.

Rosskopf, E. N., Chellemi, D. O., Kokalis-Burelle, N., and Church, G. T. 2005. Alternatives to methyl bromide: A Florida perspective. Plant Health Progress. doi:10.1094/PHP-2005-1027-01-RV.

Rosskopf, E. N., Kokalis-Burelle, N., Butler, D., and Fennimore, S. 2010. Evaluation of steam for nematode and weed control in cut flower production. Pp. 83.1–83.3. Proceedings of the Annual International Conference on Methyl Bromide Alternatives.

Samtani, J. B., Gilbert, C., Weber, J. B., Subbarao, K. V., Goodhue, R. E., and Fennimore, S. A. 2012. Effect of steam and solarization treatments on pest control, strawberry yield, and economic returns relative to methyl bromide fumigation. HortScience 47(1):64–70.

Stapleton, J. J. 2000. Soil solarization in various agricultural production systems. Crop Protection 19:837–841.

Triolo, E., Materazzi, A., and Luvisi, A. 2004. Exothermic reactions and steam for the management of soil-borne pathogens: Five years of research. Advances in Horticultural Science 18(2):89–94.

Van Loenen, M. C. A., Turbett, Y., Mullins, C. E., Feilden, N. E. H., Wilson, M. J., Leifert, C., and Seel, W. E. 2003. Low temperature-short duration steaming of soil kills soil-borne pathogens, nematode pests and weeds. European Journal of Plant Pathology 109(9):993–102.

Zasada, I. A., Elmore, C. L., MacDonald, J. D., Ferris, H., Roncoroni, J. A., Bolkan, L. R., and Yakabe, L. A. 2003. Field application of brassicaceous amendments for control of soilborne pest and pathogens. Plant Health Progress. doi:10.1094/PHP-2003-1120-01-RS.

Zasada, I. A., Halbrendt, J. M., Kokalis-Burelle, N., LaMondia, J., McKenry, M. V., and Noling, J. W. 2010. Managing nematodes without methyl bromide. Annual Review Of Phytopathology. doi:10.1146/annurev-phyto-073009-114425.