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Effects of long-term organic amendments and soil sanitation on weed and nematode populations in pepper and watermelon crops in Florida

Monica Ozores-Hampton [a,*], Robert McSorley [b], Philip A. Stansly [a]

[a] University of Florida, Southwest Florida Research and Education Center, 2685 State Road 29 North, Immokalee, FL 34142-9515, USA
[b] University of Florida, Department of Entomology and Nematology, P.O. Box 110620, Gainesville, FL 32611-0620, USA

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ABSTRACT

Florida vegetable growers have relied on methyl bromide (MeBr) fumigation to manage soil pathogens, nematodes, and weeds. This system combined with raised beds, polyethylene mulch, and seepage and/or drip irrigation has been effective for producing high vegetable yields. Alternatives to MeBr such as solarization and organic amendments have given favorable results in small trials, but there are few large-scale studies. The objectives of this study were to evaluate the effects of long-term organic amendment applications and soil sanitation treatments on weed and nematode populations on pepper (*Capsicum annuum* L.) and watermelon (*Citrullus lanatus* [Thunb.] Manst.). During 1998 and 1999 fall vegetable seasons, main plots received a yearly organic amendment (biosolids) application or a non-amendment control, with sub-plots consisting of soil sanitation treatments with solarization, MeBr, Telone® (1,3-dichloropropene), or a non-fumigated control. Each sub-plot was further divided into two sub-sub-plots, one receiving additional weed and without control weed control. During the solarization period (60 d in 1998–1999; 90 d in 1999–2000), percent weed cover was higher in the non-biosolid plots than the biosolid plots for the first part of the solarization period, but there were no differences during the last 30 days in both seasons. Purple nutsedge was able to germinate on the north edge of the beds for a border effect; a point of vulnerability when beds run east–west. With the pepper crop, the number of weeds and percent weed cover were greater in the non-fumigated plots and Telone®-treated plots than in plots treated with MeBr or in solarized plots with and without biosolids. Nematode population densities from plot to plot within the site were highly variable, which likely accounted for the relatively few consistent effects from treatments observed during the experiment. The data do provide some indication of the importance of weeds in the recovery and buildup of nematode populations. During spring 1999, both root-knot and stubby-root nematodes were more abundant in the sub-sub-plots that had not received weed control. The results suggest that solarization and organic amendments can be viable alternatives to MeBr. However, MeBr produced the most consistent results.

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1. Introduction

Intensive vegetable production systems utilizing MeBr (Bromomethane)/Chloropicrin (Trichloronitromethane;Ch) fumigation with raised beds, polyethylene mulch, and high fertilization levels have provided excellent vegetable crop yields in many areas, including south Florida (Olson and Simonne, 2007). However, MeBr production was terminated in the USA in 2005 and the product will be available to conventional vegetable growers only until the reserves become depleted (Noling and Becker, 1994; Spreen et al., 1995). Other chemical products may serve as acceptable alternatives for many vegetable growers, although none of those presently available can provide the similar benefits of MeBr as a soil fumigant. Furthermore, chemical alternatives are expensive and subject to further regulation (MacRae and Noling, 2010; MacRae et al., 2010; Spreen et al., 1995).

Non-chemical alternatives to MeBr fumigation such as solarization and organic amendments have provided favorable results in small trials, but relatively few large-scale studies have been reported (Ozores-Hampton et al., 2000, 2002). Weed seed germination and seedling growth can be suppressed at high soil temperatures (Horowitz, 1980). Solarization with clear plastic and UV-absorbing clear plastic can raise soil temperatures to 45 °C, which is above the thermal death point for most weed seedlings (Horowitz, 1980). Soil moisture increases soil heat conductivity and sensitizes seeds to high temperatures. Clear plastic mulch decreased pigweed (*Amaranthus retroflexus* L.) populations within

* Corresponding author.
E-mail address: ozores@ufl.edu (M. Ozores-Hampton).

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two weeks to less than 10% for one year (Horowitz et al., 1983), demonstrating the sensitivity of annual weeds to solarization. Solarization has also been demonstrated to be effective for controlling yellow and purple nutsedge (*Cyperus esculentus* L. *and rotundus* L.), which are difficult to control with conventional methods (Chellemi, 1995 and Chellemi et al., 1996). In addition, solarization has been widely used to manage plant-parasitic nematodes in vegetable crops (Candido et al., 2008), and has performed well in the field under Florida conditions for this purpose (McSorley and McGovern, 2000; Saha et al., 2007).

The most common destination of solid waste in the United States is incineration or landfills (Goldstein, and Madtes, 2001; Ozores-Hampton et al., 1998). When properly treated and managed in accordance with the existing state and federal regulations and standards, organic waste can be utilized as soil organic amendment after undergoing the composting process or other means of stabilization (Ozores-Hampton et al., 1998; Ozores-Hampton and Peach, 2002). Application of composted biosolids, municipal solid waste (MSW), yard trimmings or food waste compost as organic amendments to soils in vegetable production can increase plant growth and produce comparable crop yields with less inorganic nutrients than a standard commercial synthetic fertilizer (Ozores-Hampton et al., 1998, 2005 and Ozores-Hampton, 2006).

Organic amendments may be useful in weed management since phytotoxic substances such as ammonia generated by biosolids can cause delayed seed germination or cause weed seedling and plant death (Ozores-Hampton, 1998). Also, the heat and carbon dioxide (CO_2) released during decomposition of biosolids can cause weed stunting and chlorosis (Ozores-Hampton, 1998). Organic amendments may also helpful in the management of plant-parasitic nematodes (Oka, 2010), although the efficacy of biosolids has been inconsistent (Zasada et al., 2007, 2008). Biosolids used in these studies were designated as Class B because the pathogens were detectable but have been reduced to levels that do not pose a threat to public health and the environment as long as actions were taken to prevent exposure to the biosolids after their use or disposal (USEPA, 1994, 1995 and 1999). For the use of biosolids in vegetable production, state regulations, management practices and site restriction are more restrictive than for field crops. These restrictions can limit the use of vegetables receiving biosolids. For example, crops with a harvested part that touches the biosolids/soil mixture shall not be harvested for 14 months after application of biosolids. Therefore, most vegetable crops with a short production cycle (less than 150 days) cannot utilize this type of biosolids (USEPA, 1994, 1995 and 1999). In contrast, if the harvested part of the crop does not touch the biosolids/soil mixture, the restriction is that the crop shall not be harvested for 30 d after application of biosolids (plastic beds can be a physical barrier to contact). Therefore, any crops grown in plastic beds can use Class B. When properly treated and managed in accordance with the existing state and federal regulations and standards, biosolids are safe for the environment and human health (USEPA, 1999).

Therefore, the objective of this study was to evaluate the effects of biosolids as long-term organic amendment application and soil fumigation on weed and plant-parasitic nematode populations in pepper and watermelon crops in southwest Florida.

2. Materials and methods

Field experiments were conducted during the 1998–1999 growing season and the 1999–2000 growing season at the University of Florida's Southwest Florida Research and Education Center in Immokalee in a 1.8-ha field. These seasons will be referred to as the 1998 and 1999 growing seasons, respectively. The soil was Immokalee fine sand (sandy, siliceous, hyperthermic Arenic Haplaquods). Main plots of organic amendments and sub-plots of soil sanitation with four replications had been maintained since 1993. Different organic amendments (Table 1) were applied every year to simulate organic amendments available to growers throughout a long-term application. The present experiment utilized three levels of treatments in a split-split-split randomized complete block design with four replications. These were: a) two main plot treatments (organic amendments), consisting of one application of biosolids per year or an untreated control; b) three (1998) or four (1999) sub-plot treatments (soil sanitation), consisting of MeBr and Telone® located in the fumigated section of the sub-plots and solarization and untreated control plots located in the non-fumigated section of the sub-plots; and c) two sub-sub-plot treatments, with or without weed control.

2.1. Biological and chemical biosolids characteristics

Class B biosolids (anaerobic biological digestion and mechanically dewatered) were obtained from the Miami-Dade Water and Sewer Department, Miami, FL. Three samples were taken two weeks before biosolids were field-applied, and analyzed for chemical and physical properties at the Soil and Water Science Department, Univ. of Florida, Gainesville. Moisture content was estimated by oven-drying 10 g (wet weight) at 105 °C for 24 h. Total N and C concentrations were measured in biosolid samples that were air-dried for 4 d, ground in a Spex 8000 Mixer/Mill, and combusted at 1010 °C in a Carlo-Erba NA-1500 C/N/S analyzer. The biosolid samples were acid-digested and analyzed by Inductively Coupled Argon Plasma Spectroscopy (ICAP). Total nutrients and trace metals were analyzed according to EPA Method 3050 (USEPA, 1990). Electrical conductivity (EC) and pH were measured using a 2:1 (by volume) water-to-soil suspension.

2.2. Field experiments

Experimental plots were naturally infested with high populations of purple nutsedge (*C. rotundus* L.). Pepper 'X 3R Aladdin' (Peto Seed, Saticoy, CA) was grown in the 1998 and 1999 season and watermelon 'Summer Flavor 800' (Abbott and Cobb Inc., PA) as a second crop for the 1999 season. No second crop was grown for the 1998. Raised beds were formed during the middle or early summer each year, and solarization of the beds began 23 July 1998 and 1 June 1999 and continued for 60 and 90 d, respectively, using clear high-density 0.75-mil polyethylene containing UV light inhibitors (Sonoco Products Co., Orlando, FL). Soil moisture was maintained at field capacity during the solarization period in both seasons. Solarization time was extended in the second year to obtain greater weed control of yellow and purple nutsedge. Biosolids class B were applied at bed formation (10 September 1998 and 30 August 1999) at the rate of 37 and 48 Mg ha^{-1} for each treatment for the 1998 and 1999 seasons, respectively, based on crop nutrient requirements (Hochmuth and Maynard, 1998). Higher rates of biosolids were applied during the second year to

Table 1
History of organic amendments applied to the soil of field site in Immokalee, FL, during 1993–1999 seasons.

Year	Organic amendments	Rate (Mg ha^{-1})	Source
1993	Municipal solid waste compost	180	Broward County, FL
1994	Biosolids	8	Tampa, FL
1995	Yard trimmings and biosolids compost	23	Palm Beach, FL
1996	Yard trimmings and biosolids compost	45	Palm Beach, FL
	Cow manure	27	Oxford, FL
1997	Yard trimmings and biosolids compost	45	Palm Beach, FL
1998	Biosolids (Class B)	38	Miami, FL
1999	Biosolids (Class B)	47	Miami, FL

provide for the second (watermelon) crop. Treatments with MeBr (98%) and Chloropicrin (2%) were applied on 10 September 1998 and 30 August 1999 at the rate of 336 kg ha^{-1}. Telone® C35 (Dow AgroSciences, IN), consisting of 1,3-dichloropropene (61%) and chloropicrin (35%), was applied at the rate of 327 kg ha^{-1} on 30 August 1999. All beds were covered with white-faced black polyethylene mulch, including solarized beds that had clear plastics previously. Weed control in the sub-sub-plots around the beds was done by swiping manually with glyphosate (Roundup Ultra Max, Monsanto, St. Louis, MO) at 0.25 kg ha^{-1} a.i. as needed.

Plants were irrigated with a combination of drip and seepage irrigation. A 0.25-mm biwall type drip irrigation tubing was used with flow rates of 3.65 m^2 d^{-1} positioned in the center of the bed prior to mulch application. Emission points were spaced 30 cm apart. Drip irrigation duration was applied for 1 h, twice per d. Irrigation amounts were based on tensiometer readings to maintain soil–water potential greater than −15 kPa. Tensiometers were located in the plant rows at 30 and 60 cm depths in the organic amendment plots and non-organic amendments plots and monitored twice per week.

Pepper crops were transplanted 24 Sept. 1998 and 5 Oct. 1999 into raised beds, 80 m long, 0.81 m wide, 0.1 m high, with 1.8 m between centers. Sub-plots were 65 m long and weed control sub-sub-plots were 30 m long. Pepper plant spacing was 25 cm within double rows spaced 45 cm apart giving a plant population of 43,200 plants ha^{-1}. Yellow and green peppers were harvested three times during the 1998 season (28 Dec. 1998, 2 Feb. and 20 Apr. 1999) and green pepper twice during the 1999 seasons (11 Jan. and 7 Feb. 2000). On 28 Feb. 2000, watermelons were planted into the beds where the pepper crop had grown. Spacing was 1.8 m between plants, giving 3136 plants ha^{-1}. Watermelons were harvested three times: 22 May, 30 May and 12 Jun. 2000.

Inorganic N and K applications were reduced by 50% of the estimated N content applied biosolids to compensate for the N mineralized in plots receiving organic amendments. The Florida Department of Agriculture and Consumer Service interim Best Management Practice (BMP) rule states that the contribution of plant-available N from organic amendments shall be 50% of the total nitrate (NO_3) concentration of the material (FDACS, 1995). Additionally, mineralization studies of this type of biosolids concluded a 50% rate of mineralization per year (Obreza and Ozores-Hampton, 2000). Therefore, the NO_3 contributions from biosolids applied at rates of 37 and 48 Mg ha^{-1} for each treatment for the 1998–1999 and 1999–2000 season, were estimated at 282 kg ha^{-1} and 348 kg ha^{-1}, respectively. Under South Florida environmental conditions, a very low extractable amount of soil NO_3 is present in the soil; therefore we assumed no N contribution from previous organic amendments application (Hochmuth and Maynard, 1998).

Peppers and watermelon grown in the biosolid and non-biosolid plots received no P application, since soil P level was very high based on soil analysis and UF/IFAS recommendations (Hochmuth and Maynard, 1998). Inorganic fertilizer was applied to pepper by injection through the drip irrigation system at 428N–0P–178K and 377N–0P–157K kg ha^{-1} for the non-biosolid treatments and at 214N–0P–90K and 188N–0P–89K kg ha^{-1} for the biosolid plots in the 1998 and 1999 seasons, respectively. Fertilizer rates applied to watermelon by injection though the drip irrigation system were 211N–0P–88K for the non-biosolid and 106N–0P–44K for the biosolid plots in the 1999 seasons. Plants were monitored for insects and diseases, and pesticides were applied as needed, according to Univ. of Florida Extension guidelines (Hochmuth and Maynard, 1998).

2.3. Data collection

Soil samples for nematode analysis were collected at the end of each solarization period and at the end of each crop. Each soil sample consisted of 10 soil cores 2.5 cm in diameter × 20 cm deep collected from the root zones of plants or from the center of the bed when no plants were present. Soil cores comprising a sample were mixed and combined into a plastic bag. Samples were transported overnight in insulated coolers to the University of Florida campus in Gainesville, where 100-cm^3 sub-samples were removed for extraction using a sieving and centrifugation procedure (Jenkins, 1964). Additionally, 10 plants per plot were removed on 3 May 1999 and six per sub-sub-plot on 26 June 2000 and root systems rated for galling on a 0–10 scale (Zeck, 1971).

Weed evaluations during solarization were made from ten sub-samples (0.25 m^2) per treatment at 30, 60 and 30, 60, 90 d after treatments (DAT) during summer 1998 and 1999 seasons, respectively. Also, dominant weed species were recorded. Number of weeds and percent weed cover observations on pepper was made from seven sub-samples (0.25 m^2) per treatment every 15 days during the 1998 and 1999 seasons. There was no weed evaluation during the watermelon crop, since vines cover reduced the weed population.

Temperature in the soil beds was measured using a network of thermocouples, multiplexers, and dataloggers. Thermocouples were placed at the soil surface and at 5, 10, 15 and 20 cm depths below the surface in the biosolids and non-biosolids plots. Data loggers collected hourly average temperature for each treatment. The data was then processed into accumulated number of hours over 40, 45, 50, and 55 °C.

Weed data collected during solarization were subjected to analysis of variance (ANOVA) with mean separation according to Student's *t*-Test to compare results from biosolids and non-biosolids plots. Weed numbers and percent cover were subjected to repeated measures ANOVA with mean separation according to Student's *t*-Test to compare results from biosolids and non-biosolids plots during the pepper and watermelon 1998 and 1999 seasons. Weed cover percentage was transformed by Arcsin distribution before the ANOVA to obtain a normal distribution (SAS version 9.1, SAS Institute Inc., Cary, NC, 2009). In some cases, nematode data were analyzed using a split-plot analysis, with compost treatments as main plots and soil sanitation as sub-plots. In other instances, weed control treatments were included as sub-sub-plots. Data from May 1999 were analyzed as a split-split plot, using only two soil treatments (solarization, control). Data from MeBr-treated sub-plots (which were not split by weed control), were compared to the other soil treatments by single degree of freedom orthogonal contrasts. In all cases, nematode data were transformed by $\log_{10}(x + 1)$ prior to analysis, but untransformed data are presented. Nematode data are usually not normally distributed, so the normalizing log-transformation is recommended (Proctor and Marks, 1975).

3. Results

3.1. Chemical properties of biosolids

The biosolids had near neutral to alkaline pH values, C:N ratios below 20, and high EC, moisture, N, P, Ca, and micronutrient levels, but K content was low (Table 2). Phosphorous content was highest in biosolids applied in 1998 and 1999. Micronutrients such as Mg, Fe, and Mn and heavy metals such as Cd, Cu, Pb, Ni, and Zn were within the normal range for organic amendments crop application (USEPA, 1994). Pollutant concentrations of the biosolids Class B were below maximum acceptable levels under Florida Department of Environmental Protection (FDEP, 1989) and Federal level under Clean Water Act Section 503 (USEPA, 1994, 1995).

Table 2
Chemical analysis of biosolids (Class B) used during 1998 and 1999 seasons.

Characteristics	1998	1999
(% dry weight)		
C	32	36
N	4.4	5.7
P	2.2	2.7
K	0.10	0.14
Ca	6.4	6.0
(mg kg^{-1} dry weight)		
Mg	6405	8345
Fe	10,550	13,150
Cd	7.5	7.2
Cu	492	627
Mn	45	40
Pb	118	98
Ni	44	153
Zn	1051	1395
Additional properties		
Moisture (%)	79	74
C:N ratio	7.3	6.4
pH	8.1	8.6
E.C. (DS m^{-1})	12.9	14.5

3.2. Soil temperature

During the 1998 season, the number of accumulated hours at various temperature intervals over 40 °C, and the total numbers of hours with soil temperatures >40 °C, were higher at all depths in the non-biosolid plots than biosolid-amended plots, except for the 20-cm depth (Table 3). An average of 225.9 w-m^{-2} solar radiation was measured during the solarization period (http://fawn.ifas.ufl.edu/data/reports/). During the 1999 season, the number of accumulated hours at various temperature intervals over 40 °C and the total numbers of hours with soil temperatures >40 °C, were higher in biosolid plots than non-biosolid, but lower at the 10 (45–55 °C), 15 and 20 (40–45 °C) cm depths. A mean 221.5 w-m^{-2} solar radiation was registered during this period (http://fawn.ifas.ufl.edu/data/reports/). Extending the solarization period from 60 (1998) to 90 (1999) days increased the soil temperature hours accumulated at 40 °C, 45 °C and total number of hours over 40 °C by 125%, 60%, and 98% respectively, in biosolid plots, but only by 60% between 40 and 45 °C, and 14% for total number of hours over 40 °C in non-biosolid plots. In fact, a significant reduction in the 1999 as compared to the 1998 season occurred in the number of hours accumulated between 45–50 °C, 45–55 °C, and over 55 °C in non-biosolid plots.

Table 3
Effects of organic amendments on cumulative hours within various temperature ranges at different bed soil depths during solarization in 1998 (60 d) and 1999 (90 d) seasons.

Depth (cm)	40–45 °C		46–50 °C		51–55 °C		>55 °C		Total hours >40 °C	
	BS[a]	NBS[b]	BS	NBS	BS	NBS	BS	NBS	BS	NBS
Number of hours, season 1998										
0	145	202	83	153	27	92	2	44	257	491
5	145	189	65	85	8	15	0	0	218	289
10	97	139	14	31	0	0	0	0	111	170
15	47	76	0	0	0	0	0	0	47	76
20	29	19	0	0	0	0	0	0	29	19
Total	463	625	162	269	35	107	2	44	662	1045
Number of hours, season 1999										
0	305	265	116	73	16	4	0	0	437	342
5	365	330	123	103	4	0	0	0	492	433
10	253	247	13	16	0	0	0	0	266	263
15	109	131	0	0	0	0	0	0	109	131
20	7	22	0	0	0	0	0	0	7	22
Total	1039	995	252	192	20	4	0	0	1311	1191

[a] BS: Biosolids.
[b] NBS: Non-biosolids.

3.3. Weeds during solarization

Purple nutsedge was the only weed species that was observed during the solarization periods in both years and resulted from the naturally infested history of the field. Percent weed cover and number of weeds per unit area was consistently higher in the non-biosolid plots than the biosolid plots in both years, and significantly so for the first 30 d in 1998 and the first 60 d in 1999 (Table 4). However, purple nutsedge was able to germinate on the north edge of the beds indicating a lower temperature or border effect; a point of vulnerability when beds run east–west. No significant differences were found between biosolid and non-biosolid treatments during the last 30 d of the solarization period in both seasons.

3.4. Weeds in peppers

Significant interactions ($P \leq 0.05$) were observed between biosolid and soil sanitation treatments for weed numbers and percent weed cover in pepper crops in both seasons. During the 1998 season, weed numbers in the absence of fumigation were higher in biosolid plots than non-biosolid plots (Table 5). However, percent weed cover in solarized sub-plots was higher in non-biosolid plots compared to biosolid plots. Fewer weeds and lower percent weed cover were seen the first year in MeBr and solarized plots compared to the non-fumigated plots with and without biosolids.

During the 1999 season, weed numbers and percent cover were higher in the biosolid plots in MeBr and Telone® sub-plots compared to non-biosolid plots (Table 5). More weeds and higher percent weed cover were seen in non-fumigated sub-plots compared to MeBr and solarized sub-plots with and with and without biosolids. There were no differences between non-fumigation and Telone®, either in weed number or percent weed cover with and without biosolids. However, Telone® alone without biosolids resulted in fewer weeds than the no-fumigation. Weed species originated mostly in the planting holes, but some were able to cover other parts of the bed and included common ragweed (*Ambrosia artemissifolia* L.), cutleaf evening primrose (*Oenothera laciniata* Hill), flase daisy (*Eclipta prostrata* L.), narrowleaf cudweed (*Gnaphalium falcatum* Lam), eastern black nightshade (*Solanum ptycanthum* Dunal), pigweed (*A. retroflexus* L.), old world diamond (*Hedyotis corymbosa* L.), and grasses such as goosegrass (*Eleusine indica* L. Gaertn.) and large crabgrass (*Digitaria sanguinalis* (L.) Scop.). The exception was purple nutsedge which was able to push through the polyethylene mulch throughout the beds.

3.5. Nematodes in peppers and watermelon

Plant-parasitic nematodes found at this site included ring (*Mesocriconema* spp.), root-knot [*Meloidogyne incognita* (Kofoid &

Table 4
Effects of soil amendments on percent ground cover and number of weeds during solarization. Weed evaluations were made from ten sub-samples (0.25 m^2) per treatment at 30 (Aug.), 60 (Sept.) and 30 (Jun.), 60 (Jul.), 90 (Aug.) days after treatments (DAT) during summer 1998 and 1999 seasons, respectively.

Amendments	Season 1998–1999		Season 1999–2000		
	Weed cover (%)		Weed number		Weed cover (%)
	August	September	June	July	August
Biosolids	4.9	9.8	2.3	3.0	2.1
Non-biosolids	24.2**	18.3	5.8*	5.5**	4.7

**, *Significant differences from corresponding values for amendments at $P \leq 0.01$, $P \leq 0.05$, respectively. For each variable, means in rows with the same letter are not significantly different by Tukey's Range Test ($P \leq 0.05$).

Table 5
Interactions of soil amendments and soil sanitation on numbers of weeds and percentage weed cover during the pepper crops. Number of weeds and percent weed cover on pepper was made from seven sub-samples (0.25 m^2) per treatment every 15 days during the 1998 and 1999 seasons.

Amendments	Weed number/0.25 m^2				Weed cover (%)			
	Methyl bromide	Solarization	Telone®	Non-fumigated	Methyl bromide	Solarization	Telone®	Non-fumigated
1998–1999								
Biosolids	0.97b	3.08b	–	12.23a**	20.86b	23.02b*	–	45.94a
Non-biosolids	0.85b	3.06b	–	6.76a	15.99c	43.42b	–	61.50a
1999–2000								
Biosolids	0.67b	0.79b	4.87a**	7.82a	7.73bc**	4.42c	30.88ab**	36.11a
Non-biosolids	0.61b	1.01b	3.39b	8.98a	1.97b	4.53b	14.56ab	31.87a

**, *Significant differences from corresponding values for amendments at $P \leq 0.01$, $P \leq 0.05$, respectively. For each variable, means in rows with the same letter are not significantly different by Tukey's Range Test ($P \leq 0.05$).

White)] Chitwood, sheath (*Hemicycliophora* spp.), and stubby-root [*Paratrichodorus minor* (Colbran) Siddiqi] nematodes. Root-knot nematodes were not detected in any of the plots in October 1998, and solarization appeared to have no impact on ring or sheath nematodes (Table 6). Sheath nematode populations were significantly lower ($P \leq 0.05$) in plots that had received biosolids (Table 6), however this nematode fell to low levels (<1.0 per 100 cm^3 soil) in all plots on subsequent sampling dates.

Root-knot nematodes increased to high levels by May 1999 (Table 7). When biosolids, soil sanitation (excluding MeBr), and weed control treatments were analyzed as a split-split plot, a significant ($P \leq 0.05$) biosolids × soil sanitation treatment interaction on nematode numbers was observed. Highest populations of root-knot nematodes were found in treatments that were both solarized and received biosolids (Table 7). Root-gall ratings were somewhat lower ($P \leq 0.05$) in MeBr-treated plots compared to solarized or non-fumigated plots (Table 7).

Following termination of the pepper crop in May 1999, nematode populations then declined over the summer of 1999. At the beginning of the pepper crop in fall 1999, the relatively low populations of ring nematodes present (mean = 4.0/100 cm^3 soil in control treatment) were reduced to near zero (0.1–0.2/100 cm^3 soil) by soil fumigation treatment with MeBr or Telone® (data not shown). By the end of the fall crop, numbers of root-knot nematodes had recovered, but root-galling was still very low (mean = 0.9 in control treatment). Low numbers (≤2.9/100 cm^3 soil in control plots) of ring and stubby-root nematodes were present as well. No significant effects of treatment on any nematode species were observed in the pepper crop due to the highly variable distribution of nematodes from plot-to-plot, especially root-knot nematodes (data not shown).

By the end of the spring watermelon crop, ring nematodes reached higher levels in control plots than in plots receiving any other treatment (Table 8; significant soil sanitation treatment effect). Stubby-root nematodes were generally unaffected by soil sanitation treatments. However, an orthogonal contrast between sub-plots indicated higher ($P \leq 0.05$) numbers of stubby-root nematodes in plots without weed control (6.3 per 100 cm^3 soil) compared to plots that received weed control (1.8 per 100 cm^3 soil). Significant interactions of biosolids with soil sanitation and weed control were observed for root-knot nematodes ($P \leq 0.05$). In plots amended with biosolids, root-knot nematodes were least abundant with solarization, but in plots without biosolids, the fewest root-knot nematodes were recorded from Telone®-treated plots (Table 8). Root-knot nematodes were much more abundant in biosolid plots without weed control than in those with weed control, while there was no effect of weed control in non-biosolid plots (Table 8). No effects of any treatment or their combinations were observed for root-gall ratings, which averaged 2.1 across all plots (data not shown).

4. Discussion

During solarization, higher temperatures in the biosolid plots during the 1999 season were probably due to higher soil organic matter (SOM) content in the bed, therefore higher available water holding capacity which improved the soil heat conductivity. Thermal sensitivity for vascular plants such as weed is about 45 °C (Chellemi, 1995), which was achieved during the solarization period in biosolid and non-biosolid plots for both years. Although temperatures during solarization were lower in the 1998 season, the reduction in weeds was significantly greater in biosolid than non-biosolid plots for both years. Thermal sensitivity can be

Table 6
Effect of biosolids amendment and soil sanitation treatment on population densities of plant-parasitic nematodes (number/100 cm^2) near beginning of pepper crop (8 October 1998).

Soil sanitation	Nematodes per 100 cm^3 soil		
	Biosolids	Non-biosolids	Mean
Ring nematodes			
Methyl bromide	0.2	3.0	1.6a
Solarization	7.0	22.5	14.8b
Control	35.0	18.8	26.9b
Mean	14.1A	14.8A	
Sheath nematodes			
Methyl bromide	0	0.2	0.1a
Solarization	0.2	4.5	2.4ab
Control	1.0	6.2	3.6b
Mean	0.4A	3.7B	

For each nematodes, main effect means in columns (a, b) or in rows (A, B) followed by the same letter do not differ at $P \leq 0.05$. No interactions were significant at $P \leq 0.10$.

Table 7
Effect of biosolids amendment, soil sanitation treatment, and weed control on population densities of root-knot nematodes (number/100 cm^2) and root-gall ratings at end of pepper crop (3 May 1999).

Soil sanitation	Biosolids			Non-biosolids			Mean
	Weed control	No weed control	Mean	Weed control	No weed control	Mean	
Root-knot nematodes per 100 cm^3 soil							
Solarization	459	1062	760aA[a]	340	360	350aB	555
Control	362	238	300bA	528	392	460aA	380
Mean	410	650	530	434	376	405	
Methyl bromide			1659			333	996
Root-gall rating[b]							
Solarization	5.8	5.9	5.8	5.6	6.2	5.9	5.9*
Control	5.5	5.6	5.5	6.0	5.7	5.8	5.7*
Mean	5.6	5.7	5.7	5.8	5.9	5.9	
Methyl bromide			4.8		4.6		4.7

*Mean differs ($P \leq 0.05$) from corresponding mean for methyl bromide treatment, according to orthogonal contrast.
[a] Significant ($P \leq 0.05$) compost × treatment interaction; means in columns (a, b) or in rows (A, B) followed by the same letter do not differ at $P \leq 0.05$.
[b] Root-galls rated on a scale from 0 (none) to 10 (severe) (Zeck, 1971).

Table 8
Effect of biosolids amendment, soil sanitation treatment, and weed control on population densities of plant-parasitic nematodes at end of watermelon crop (June 2000).

Soil sanitation	Nematodes per 100 cm^3 soil						Mean
	Biosolids			Non-biosolids			
	Weed control	No weed control	Mean	Weed control	No weed control	Mean	
Ring nematodes							
Methyl bromide	0	0	0	0	0	0	0b
Telone®	0	0	0	1.2	0.2	0.8	0.4b
Solarization	0	0	0	1.8	2.8	2.2	1.1b
Control	0.5	3.0	1.8	4.5	13.8	9.1	5.4a
Mean	0.1	0.8	0.4	1.9	4.2	3.0	
Root-knot nematodes							
Methyl bromide	8.5	51.8	30.1a	22.5	7.0	14.8ab	22.4
Telone®	12.0	122.5	67.2a	3.0	1.8	2.4b	34.8
Solarization	2.0	2.8	2.4b	32.5	15.8	24.1a	13.2
Control	11.5	67.5	39.5a	9.2	27.8	18.5a	29.0
Mean	8.5A	61.1B	34.8	16.8A	13.1A	14.9	
Stubby-root nematodes							
Methyl bromide	0	8.2	4.1	0.8	3.0	1.9	3.0
Telone®	0.8	3.8	2.2	2.2	4.0	3.1	2.7
Solarization	1.0	5.0	3.0	3.8	4.2	4.0	3.5
Control	0.5	12.0	6.2	5.5	10.0	7.8	7.0
Mean	0.6	7.2	3.9	3.1	5.3	4.2	

Means in columns (a, b) or in rows (A, B) followed by the same letter do not differ at $P \leq 0.05$.

influenced by other factors such moisture content in the soil, which was probably higher due to higher SOM content in the soil in the biosolid plots than non-biosolid plots (Ozores-Hampton et al., 2011). Also, biosolids with low C:N ratio can produced phytotoxins such as ammonia that can reduce weed populations (Ozores-Hampton, 1998; Ozores-Hampton et al., 2001; Hadar et al., 1985; Jimenez and Garcia, 1989).

Our results show that soil solarization can be effective against purple nutsedge, which along with yellow nutsedge (*C. esculentus* L.) can be difficult to control with conventional methods (Chellemi, 1995). But, the point of vulnerability in our system was the north edge side of the bed running in the east–west direction. Because this north edge of the bed does not receive direct sunlight over the course of the day, soil temperatures are typically lower there than on the top of the raised bed, allowing weeds growth to begin on the north wall of the bed (McGovern et al., 2004).

Extending the solarization period from 60 (1998) to 90 (1999) d produced lower percent weed cover in the 1999 than in the 1998 season. The extended solarization period brought weed control up to the same standard as MeBr during the second season. Biosolids reduced weeds in non-fumigated and Telone® fumigated plots, and reduced weed cover in solarized plots the first year, even though accumulated temperatures during solarization were higher at all depths in the non-biosolid plots than in biosolid plots (Table 3). Again, these effects could be attributed to effects of higher moisture content together with production of phytotoxins in low C:N ratio composts.

Nematode population densities were highly variable from plot to plot, which likely accounts for the relatively few consistent effects from treatment observed during this experiment. One limitation in the performance of solarization against root-knot nematodes may have been the length of the susceptible crop cycles (7 mo for the pepper crop in 1998, almost 9 mo for the pepper-watermelon double crop in 1999). Typically solarization will suppress nematodes for 3–4 mo on short-term crops (McGovern et al., 2002), but root-knot nematodes recover after 6 mo on a susceptible crop or double crop (McSorley et al., 2009; Overman and Jones, 1986). The data do provide some indication of the importance of weeds in the recovery and buildup of nematode populations. In the spring crop of the 1999 season, both root-knot and stubby-root nematodes were more abundant in the sub-sub-plots that had not received weed control (Table 7).

Overall, solarization together with organic amendments had substantial suppressive effect especially on weeds, and could be considered an attractive alternative to MeBr. However, the performance of MeBr was more consistent, especially against nematodes. Future research should focus on optimizing and improving the consistency of important non-chemical alternatives like solarization and organic amendments.

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References

Candido, V., D'Addabbo, T.D., Basile, M., Castronuovo, D., Miccolis, V., 2008. Greenhouse soil solarization: effect on weeds, nematodes and yield of tomato and melon. Agron. Sustain. Dev. 28, 221–230.
Chellemi, D.O., Rich, J.R., Barber, S., McSorley, R., Olson, S.M., 1996. Adaptation of Soil Solarization to the Integrated Pest Management of Soilborne Pests under Humid Conditions. Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. Methyl Bromide Alternatives Outreach, Fresno, CA.
Chellemi, D.O., 1995. Soil Solarization for Management of Soilborne Pests. PPP 51, Fla. Coop. Ext. Serv., Inst. Food Agri. Sci., Univ. Fla., Gainesville, FL.
(FDACS) Florida Dept. Agriculture and Consumer Services, 1995. Development of Suggested Compost Parameters and Composting Guidelines. The Composting Council, Alexandria, VA.
(FDEP) Florida Department of Environmental Protection, 1989. Criteria for the Production and Use of Compost made from Solid Waste. Florida Administrative Code, Chapter 17–709. Tallahassee, FL.
Goldstein, N., Madtes, C., 2001. The state of garbage in America. 1999. BioCycle 42, 42–52.
Hadar, Y., Inbar, Y., Chen, Y., 1985. Effect of compost maturity on tomato seedling growth. Scientia Hort. 27, 199–208.
Hochmuth, G.J., Maynard, D.N., 1998. Vegetable Production Guide for Florida. Fla. Coop. Ext. Serv., Inst. Food Agri. Sci., Univer. Fla. SP 170.
Horowitz, M., 1980. Weed research in Israel. Weed Sci. 31, 457–460.
Horowitz, M., Regev, Y., Herzlinger, G., 1983. Solarization for weed control. Weed Sci. 31, 170–179.
Jimenez, E.I., Garcia, V.P., 1989. Evaluation of city refuse compost maturity: a review. Biol. Wastes 27, 115–142.
Jenkins, W.R., 1964. A rapid centrifugal-flotation technique for separating nematodes from soil. Plant Dis. Reporter 48, 692.
MacRae, A., Noling, J., Snodgrass, C., 2010. Maximizing the Efficacy of Soil Fumigant Applications for Raised-Bed Plasticulture Systems of Florida. 28 July, 2011. http://edis.ifas.ufl.edu/hs1169.
MacRae, A., Noling, J., 2010. Methyl Bromide Fumigant REDs Regulations Overview. 28 July, 2011. http://edis.ifas.ufl.edu/hs1166.
McGovern, R.J., McSorley, R., Bell, M.L., 2002. Reduction of landscape pathogens in Florida by soil solarization. Plant Dis. 86, 1388–1395.
McGovern, R.J., McSorley, R., Wang, K.-H., 2004. Optimizing bed orientation and number of plastic layers for soil solarization in Florida. Soil Crop Sci. Soc. Fla. Proc. 63, 92–95.
McSorley, R., McGovern, R.J., 2000. Effects of solarization and ammonium amendments on plant-parasitic nematodes. J. Nematol. 32, 537–541.
McSorley, R., Wang, K.H., Rosskopf, E.N., Kokalis-Burelle, N., HansPetersen, H.N., Gill, H.K., Krueger, R., 2009. Non-fumigant alternatives to methyl bromide for management of nematodes, soil-borne disease, and weeds in production of snapdragon (*Antirrhinum majus*). Int. J. Pest Manage. 55, 265–273.
Noling, J.W., Becker, J.O., 1994. The challenge of research and extension to define and implement alternatives to methyl bromide. J. Nematol. 26, 573–586.
Obreza, T.A., Ozores-Hampton, M.P., 2000. Management of organic amendments in Florida citrus production systems. Soil Crop Sci. Soc. Fla. Proc. 59, 22–27.
Oka, Y., 2010. Mechanisms of nematode suppression by organic soil amendments – a review. Appl. Soil Ecol. 44, 101–115.
Olson, S.M., Simonne, E., 2007. Vegetable Production Handbook for Florida 2007–2008. Vance Publishing, Lenexa, KS.
Overman, A.J., Jones, J.P., 1986. Soil solarization, reaction, and fumigation effects on double-cropped tomato under full-bed mulch. Proc. Fla. State Hort. Soc. 99, 315–318.
Ozores-Hampton, M.P., Stansly, P.A., Salame, T.P., 2011. Soil chemical, biological and physical properties of a sandy soil subjected to long-term organic amendments. J. Sustain. Agri. 35, 243–259.

Ozores-Hampton, M., 2006. Soil and nutrient management: compost and manure, Chapter 3. In: Grower's IPM Guide for Florida Tomato and Pepper Production. Univer. Fla., Gainesville, FL, pp. 36–40.
Ozores-Hampton, M., Stansly, P.A., McSorley, R., Obreza, T.A., 2005. Effects of long-term organic amendments and soil solarization on pepper and watermelon growth, yield, and soil fertility. HortScience 40, 80–84.
Ozores-Hampton, M.P., Roe, N.E., McSorley, R., Obreza, T.A., Stansly, P.A., Chellemi, D.O., 2002. Long term large scale soil solarization as a low-input production system for Florida vegetables. In: Proc. of the XXVIth International Horticultural Congress. Acta Horticulturae, pp. 638–642 (CD-ROM).
Ozores-Hampton, M., Peach, D.R.A., 2002. Biosolids in vegetable production systems. HortTechnology 12, 18–22.
Ozores-Hampton, M.P., Obreza, T.A., Stoffella, P.J., 2001. Mulching with composted municipal solid waste for biological control of weeds in vegetable crops. Compost Sci. Utilization 9, 352–361.
Ozores-Hampton, M., Stansly, P.A., Obreza, T.A., 2000. Biosolids and soil solarization effects on bell pepper (*Capsicum annuum*) production and soil fertility in a sustainable production system. HortScience 35, 443.
Ozores-Hampton, M., Obreza, T.A., Hochmuth, G., 1998. Using composted wastes on Florida vegetable crops. HortTechnology 8, 130–137.
Ozores-Hampton, M.P., 1998. Compost as an alternative weed control method. HortScience 33, 938–940.
Proctor, J.F., Marks, C.F., 1975. The determination of normalizing transformations for nematode count data from soil samples and of efficient sampling schemes. Nematologica 20, 395–406.
Saha, S.K., Wang, K.-H., McSorley, R., McGovern, R.J., Kokalis-Burelle, N., 2007. Effect of solarization and cowpea cover crop on plant-parasitic nematodes, pepper yields, and weeds. Nematropica 37, 51–63.
Spreen, T.H., VanSickle, J.J., Moseley, A.E., Deepak, M.S., Mathers, L., 1995. Use of Methyl Bromide and the Economic Impact of its Proposed Ban on the Florida Fresh Fruit and Vegetables Industry. In: Bulletin 898. Fla. Coop. Ext. Serv., Inst. Food Agri. Sci., Univer. Fla., Gainesville, FL.
(USEPA) U. S. Environmental Protection Agency, 1999. Biosolids Generation, Use, and Disposal in the United States. EPA503-R-99–009. Sept. Wash., DC.
(USEPA) U. S. Environmental Protection Agency, 1995. A Guide to the Biosolids Risk Assessments for the EPA Part 503 Rule. EPA832-B-93–005. Sept. Wash., DC.
(USEPA) U. S. Environmental Protection Agency, 1994. A Plain English Guide to the EPA Part 503 Biosolids Rule. EPA832-R-93–003. Sept. Wash., DC.
(USEPA) U. S. Environmental Protection Agency, 1990. Test Methods for Evaluating Solid Waste. EPA Report SW-846. Office of Solid Waste and Emergency Response, Wash., DC.
Zasada, I.A., Avendano, F., Li, Y.C., Logan, T., Melakeberhan, H., Koenning, S.R., Tylka, G.L., 2008. Potential of an alkaline-stabilized biosolid to manage nematodes: case studies on soybean cyst and root-knot nematodes. Plant Dis. 92, 4–13.
Zasada, I., Rogers, S., Sardanelli, S., 2007. Application of alkaline-stabilized biosolids for *Meloidogyne incognita* suppression in microplots. Nematology 91, 123–129.
Zeck, W.W., 1971. A rating scheme for field evaluation of root-knot nematode infestations. Pflanzenschutz-Nachrichten Bayer 24, 141–144.