EFFECT OF SOLARIZATION AND COWPEA COVER CROP ON PLANT-PARASITIC NEMATODES, PEPPER YIELDS, AND WEEDS

S. K. Saha[1], K.-H. Wang[2], R. McSorley[2]*, R. J. McGovern[3], and N. Kokalis-Burelle[4]

[1]Horticultural Science Department, University of Florida, Gainesville, FL 32611; [2]Department of Entomology and Nematology, University of Florida, Gainesville, FL 32611; [3]Department of Plant Pathology, University of Florida, Gainesville, FL 32611; and [4]USDA, ARS, U.S. Horticultural Research Lab, Ft. Pierce, FL 34945. *Corresponding author: mcsorley@ufl.edu

ABSTRACT

Saha, S. K., K.-H. Wang, R. McSorley, R. J. McGovern, and N. Kokalis-Burelle. 2007. Effect of solarization and cowpea cover crop on plant-parasitic nematodes, pepper yields, and weeds. Nematropica 37:51-63.

Two field experiments with bell pepper (*Capsicum annuum*) 'Wizard X3R' were established (May 2003, 2004) in Marion Co., Florida, U.S.A. The objective was to compare yields, nematode populations, and weeds as impacted by six soil management treatments: cowpea (*Vigna unguiculata*) summer cover crop, solarization on a raised bed, solarization on a flat surface, cowpea cover crop followed by raised bed solarization, methyl bromide fumigation, and untreated control. Soil samples were obtained after all treatments had been applied, just prior to planting, and at the end of the season to determine the effects of treatments on nematode population densities. In 2003 prior to planting, ring nematodes (*Mesocriconema* sp.) were most prevalent in the control treatment and lowest in the cowpea cover crop combined with raised bed solarization, and the methyl bromide fumigation treatments. At the end of both seasons the combination of cowpea cover crop with bedded solarization was as effective as methyl bromide fumigation for suppressing root-knot nematodes (*Meloidogyne* spp.). In 2004, raised-bed solarization was also as effective as methyl bromide for suppressing root-knot nematodes. All solarization treatments were effective in suppressing weeds compared to the untreated control, and were more effective than methyl bromide in 2003 when no glyphosate was applied during the summer. Solarization treatments were equivalent to glyphosate-treated methyl bromide and control plots in 2004. Pepper yields of U.S. Fancy grade and total fruit weight in 2003 were higher in raised-bed solarization than methyl bromide fumigated plots. Cowpea in combination with raised-bed solarization resulted in higher total fruit weight relative to methyl bromide fumigation. Two hurricanes followed by a *Pythium* sp. epidemic confounded yield differences in 2004. However, flat solarization resulted in greater total fruit number and weight of U.S. #1 grade peppers than methyl bromide fumigation. Solarization and solarization combined with a cowpea cover crop can be useful alternatives for nematode and weed suppression, and improved yield of pepper.

Key words: Capsicum annuum, integrated pest management, *Meloidogyne*, *Mesocriconema*, methyl bromide alternatives, ring nematode, root-knot nematode, sustainable agriculture, *Vigna unguiculata*.

RESUMEN

Saha, S. K., K.-H. Wang, R. McSorley, R. J. McGovern, y N. Kokalis-Burelle. 2007. Efecto de la solarización y uso de caupí como cultivo de cobertura sobre nematodos fitoparásitos, producción de pimiento y malezas. Nematropica 37:51-63.

Se establecieron dos experimentos con pimiento (*Capsicum annuum*) 'Wizard X3R' en Marion Co., Florida, EE.UU. (mayo 2003, 2004). El objetivo fue comparar el efecto sobre la producción, poblaciones de nematodos y malezas causado por seis tratamientos de prácticas de manejo: caupí (*Vigna unguiculata*) como cultivo de cobertura de verano, solarización en camas elevadas, solarización en superficies niveladas, caupí como cultivo de cobertura seguido por solarización en camas elevadas, fumigación con bromuro de metilo, y control sin tratamiento. Se obtuvieron muestras de suelo después de aplicar todos los tratamientos, antes de la siembra y al tiempo de cosecha para determinar los efectos de los tratamientos sobre las densidades de población de los nematodos. En 2003, antes de la siembra, los nematodos anillados (*Mesocriconema* sp.) eran los más prevalentes en el tratamiento de control y los presentes en menor cantidad en los tratamientos de cobertura de caupí combinado con solarizazión en camas elevadas, y fumigación con bromuro de metilo. Al final de ambas temporadas, la combinación de cobertura de caupí con solarización de camas fue tan efectiva como la fumigación con bromuro de metilo en supresión de nematodos del nudo radical (*Meloidogyne* spp.). En 2004, la solarización de camas elevadas también fue tan efectiva como el bromuro de metilo en la supresión de nematodos del nudo radical. Todos los tratamientos de solarización fueron efectivos en la supresión de malezas comparados con el control sin tratamiento, y fueron más efectivos que el bromuro de metilo en 2003 cuando no se aplicó glifosato durante el verano. Los resultados de la solarización fueron equivalentes a la aplicación de glifosato en las parcelas de bromuro de metilo y control en 2004. La producción de pimientos de alta calidad (U.S. Fancy grade) y peso total de frutos en 2003 fueron mayores en las camas elevadas solarizadas que en las parcelas fumigadas con bromuro de metilo. El caupí en combinación con la solarización de camas elevadas produjo mayor peso total relativo de frutos que la fumigación con bromuro de metilo. Las diferencias entre tratamientos en las pruebas de 2004 se vieron afectadas por dos huracanes y una epidemia de *Pythium* sp. Sin embargo, la solarización de suelo nivelado produjo mayor cantidad y peso total de frutos de pimiento de alta calidad que la fumigación con bromuro de metilo. La solarización y solarización combinada con caupí como cultivo de cobertura pueden ser alternativas útiles para el manejo de nematodos y malezas, y aumentar la producción de pimientos.

Palabras clave: agricultura sostenible, alternativas al bromuro de metilo, *Capsicum annuum*, manejo integrado de plagas, *Meloidogyne*, *Mesocriconema*, nematodo anillado, nematodo del nudo radical, *Vigna unguiculata*.

INTRODUCTION

Alternative and sustainable approaches to agriculture are becoming of greater interest as societal concerns about the environmental impacts of agricultural practices continue to increase. Environmental impacts associated with pesticides and other agri-chemicals have stimulated a search for alternatives (Katan and DeVay, 1991). Additionally, the environmental and health impacts of many pesticides are currently being re-evaluated (Obenauf, 2004). The imminent loss of methyl bromide, a broad-spectrum soil fumigant that is effective against weeds, soil insects, and soilborne pathogens, including nematodes, has resulted from these re-evaluations (Chellemi *et al.*, 2004; Louws *et al.*, 2004; Rodriguez-Kabana *et al.*, 2004). In Florida, much of the tomato (*Lycopersicon esculentum* L.), strawberry (*Fragaria* × *ananassa* Duch.), and other vegetable acreage is fumigated with methyl bromide. The production of methyl bromide fumigant in the United States was to end in January of 2005 due to its ozone depleting properties (U.S. EPA, 2005). However, because of the critical need for agriculture, special exemptions have been granted for its continued use and production on a yearly basis since 2005 (U.S. EPA, 2005). Research continues to examine the technical and economic feasibility of both chemical and non-chemical replacements (Obenauf, 2004).

One of the most efficient non-chemical soil management tactics is solarization (McGovern and McSorley, 1997). Clear polyethylene is used to cover a planting area instead of the opaque plastic mulch that is commonly used in the culture of many vegetables, including tomato and pepper (*Capsicum annuum* L.). Solarization can be installed in strips over the planting beds [raised-bed solarization (SRB)] or by covering the entire field with strips of plastic attached together [flat solarization (SFS)]. Prior to coverage with polyethylene, the soil is moistened to increase the effects of solar heating. Temperatures of 50°-60°C achieved by solarization are lethal to many soil pests (McGovern and McSorley, 1997). The success of solarization depends on proper installation of plastic (Dover *et al.*, 2003). While SRB is more practical for vegetable producers, soil contamination from untreated adjacent soil is minimized with SFS (McGovern *et al.*, 2004).

Solarization has been used to manage plant-parasitic nematodes in a variety of situations (Chellemi *et al.*, 1993; Heald and Robinson, 1987; Katan, 1981; McGovern and McSorley, 1997; McSorley and McGovern, 2000; McSorley and Parrado, 1986); however, it has been reported that the suppression of nematodes is not as long-lasting as that of methyl bromide fumigation (Overman and Jones, 1986). Therefore solarization is not viable as a stand-alone procedure, but has potential as a component in an integrated crop health management strategy. Solarization can be used in conjunction with crop rotation, sanitation, crop resistance, and cover cropping; which are non-chemical tactics widely utilized for nematode management (McSorley, 1998). Certain varieties of cowpea [*Vigna unguiculata* (L.) Walp.] are antagonistic to plant-parasitic nematodes (Wang and McSorley, 2004). In particular, the cultivar 'Iron Clay' is suppressive to some species of root-knot nematodes (*Meloidogyne* spp.) primarily because it is a poor host (McSorley *et al.*, 1999; Wang *et al.*, 2003). Objectives of the current experiment were to; 1) evaluate soil solarization and cowpea cover crops as alternatives to methyl bromide, 2) compare raised bed solarization with flat solarization, and 3) examine the effect of integrating cowpea cover crops with solarization for the management of plant-parasitic nematodes and weeds, and determine the impact on pepper fruit yield.

MATERIALS AND METHODS

Field Description

The experiment was conducted at the University of Florida Plant Science Research and Education Unit (29°24'N, 82°9'W), located near Citra in Marion County, FL. The soil was well drained, coarse textured (95.2% sand, 1.5% silt, 3.3% clay), and classified as an Arredondo sand (Thomas *et al.*, 1979). Prior to field preparation and planting, the land was in weed fallow.

In October 2002, the site was planted with a cover crop of 'Dixie' crimson clover (*Trifolium incarnatum* L.) inoculated with *Meloidogyne incognita* (Kofoid and White, 1912) Chitwood, 1949 race 1. The cover crop was maintained until senescence, disked, and sub-soiled twice due to the density of crop debris on 28-29 April 2003.

2003 Experiment

On 7 May 2003, a field experiment was established consisting of six treatments with six replications in a randomized complete block design on approximately 0.2 ha. The treatments included weed fallow control (UC), summer cowpea cover crop (SCC), raised bed solarization (SRB), flat solarization (SFS), summer cowpea cover crop followed by raised bed solarization (CCSRB), and fumigation with methyl bromide (MBF). The rows were oriented from east to west and individual plots were 2.44 m wide by 18.29 m long. 'Iron Clay' cowpea was purchased locally (Alachua County Feed and Seed, Gainesville, FL) and planted in rows 19-23 cm apart on 7

May at a seed density of 56 kg seed/ha. During this period, plots without cowpea were left fallow with weeds. The cowpea was irrigated by an overhead sprinkler system as needed and on 7 July 2003 they were disked and roto-tilled. Solarization treatments were established on 8 July. For bedded solarization, raised beds 0.76 m wide by 18.29 m long were formed with a tractor and covered with clear, 25-µm-thick, UV-stabilized, low-density polyethylene mulch (ISO Poly Films, Inc., Gray Court, SC). The flat solarization treatment was installed manually on flat 2.44-m-wide by 18.29-m-long plots. The plastic utilized for the flat solarization treatments was 51-µm-thick (2 mil) construction-grade plastic (Poly Film, Veri Pack, Inc., Farmington, MA) which was 2.54 m wide. Soil was irrigated prior to solarization. Soil temperatures at depths of 5 cm and 15 cm were recorded hourly using data loggers (Watch Dog® Model 425, Spectrum® Technologies, Inc., Plainfield, IL). Solarization treatments were in place for 5.5 weeks. On 15 August, the non-solarized treatments were roto-tilled and bedded, whereas in the solarized treatments the clear plastic was removed. All beds were covered with opaque, reflective plastic mulch (Sonoco Agricultural Films, Hartsville, SC). Methyl bromide (67:33; 67% methyl bromide:33% chloropicrin) was applied in the appropriate plots at 450 kg/ha.

Seedlings of 'Wizard X3R' pepper, obtained from Speedling Ornamentals (Sun City, FL), were transplanted on 9 September in double rows with spacing of 46 cm within row and 30 cm between rows, resulting in a density of approximately 75 plants per plot. From 10-16 September, transplants that died were replaced (<2% of the entire population—approximately 60 plants of >3,000 total). Water and fertilizer were applied on a daily basis through drip irrigation for a total of 202 kg N/ha for the season. Problems with foliar diseases and insects were minor and were managed by fungicides and insecticides as needed.

Peppers were harvested on 18 November, 25 November, and 9 December 2003, from 40 plants per plot and graded into the following categories: U.S. Fancy grade (size minimum of 7.62 cm in diameter and at least 8.89 cm long), U.S. No. 1 (minimum diameter and length is 6.35 cm), and U.S. No. 2 grade (size smaller than U.S. No. 1) (Sargent, 2000).

Soil samples for nematode analysis were collected from each plot at planting (9 September 2003) and at the end of the crop (9 January 2004). Six soil cores (2.5 cm diameter × 20 cm deep) were collected from each plot and combined into one composite sample. Nematodes were extracted from a 100-cm^3 sub-sample using a modified sieving and centrifugal-flotation method (Jenkins, 1964).

Weeds and cutworm (*Agrotis* sp.) damage were assessed on several occasions. On 12 August, each plot was rated for the percentage of surface area covered by weeds using the 1 to 12 rating scale of Horsfall and Barrett (1945), where 1 = 0%, 2 = 0-3%, 3 = 3-6%, 4 = 6-12%, 5 = 12-25%, 6 = 25-50% of ground covered, whereas 7 = 25-50%, 8 = 12-25%, 9 = 6-12%, 10 = 3-6%, 11 = 0-3%, and 12 = 0% of ground not covered. At the end of the experiment on 8 January 2004, weeds were evaluated by counting the number of planting holes with weeds, based on 60 plants per plot. On 7 October, the dead plants per plot caused by cutworms were counted.

2004 Experiment

On 28 April 2004, the second trial was established in precisely the same field plots as in 2003. Similar treatments were implemented with minor differences. At termination of the cowpea cover crop in

June 2004, all plots (not just those receiving cowpea treatments) were roto-tilled to suppress weeds. Prior to roto-tilling, weeds were sprayed with glyphosate in mid-June to reduce weed biomass. Solarization treatments were established on 30 June 2004 and terminated on 16 August. The methyl bromide treatment was applied 17 August and pepper seedlings were transplanted 31 August.

Two hurricanes affected the experiment in 2004. Hurricane Frances (5, 6 September) produced 41cm of rain in 24 hours, flooding the field (Division of Hydrologic Data Services, 2004; S. Taylor, pers. comm.). The following week, a severe disease epidemic occurred throughout the field and a second hurricane (Jeanne) occurred on 26 September. The number of dead plants per plot caused by the disease epidemic was reported elsewhere (Saha *et al.*, 2006).

Following the two hurricanes, the crop was managed with proper irrigation and fertilizer for the remainder of the season. The peppers were harvested and graded on 30 November, 7 December, and 14 December 2004. Due to the loss of plants, harvest was based on 60 plants per plot, and harvests were delayed approximately two weeks compared to the previous season. Soil samples for nematode analysis were collected from all plots on 29 August and 14 December 2004. Because the early summer roto-tilling greatly reduced weed populations, weeds were not measured prior to planting. However, numbers of planting holes with weeds were recorded on 26 October 2004.

Statistical Analysis

Data were subjected to one-way analysis of variance (ANOVA) using the Statistical Analysis System (SAS Institute, Cary, NC). To ensure that data fit a normal distribution prior to analysis, nematode abundance data were log-transformed by $\log_{10}(x+1)$. However, only untransformed arithmetic means of all data are presented.

RESULTS

Soil Temperatures

2003: Temperatures during solarization were similar in treatments involving solarization (SFS, CCSRB), which were higher than temperatures in cowpea (SCC) and control (UC) treatments (data not shown). At 5-cm soil depth in 2003, both SRB and CCSRB resulted in 29 days of maximum temperatures ≥42°C, whereas these temperatures were never obtained in SCC and UC.

2004: In the second experiment, the number of days with maximum temperature ≥42°C at 5 cm depth was 33 for CCSRB and 29 for SRB. Fewer days achieved this temperature at soil depths of 15 cm in S and SRB and CCSRB. In all non-solarized plots, temperatures of 42°C were reached on only two days in the SCC treatment. Data reported in the literature and the results of preliminary laboratory tests indicate that 42.5°C is the minimum soil temperature necessary to cause mortality of herbivorous nematodes such as reniform (*Rotylenchulus reniformis* Linford & Oliviera, 1940) and the southern root-knot nematode (Heald and Robinson, 1987; Wang, K.-H., unpublished).

Nematodes

2003: Prior to pepper planting, but after all treatments had been implemented, ring nematodes (*Mesocriconema* spp.) were the most prevalent nematodes found, with minor presence of spiral (*Helicotylenchus* sp.), stubby root (*Paratrichodorus* spp.), and lesion nematodes (*Pratylenchus* spp.). Ring nematodes were most prevalent ($P \leq 0.05$) in the UC treatment (Table 1). The CCSRB treatment and the MBF treat-

Table 1. Effect of soil treatments on plant-parasitic nematodes in September 2003.

	Nematodes per 100 cm^3 soil			
Treatment	Root-knot	Ring	Stubby-root	Lesion
Solarization (SRB)	0.0	4.2 c[z]	4.3 a	0.2 dc
Solarization + cowpea (CCSRB)	0.0	0.8 d	0.5 ab	0.7 bc
Flat solarization (SFS)	0.0	8.7 b	2.7 ab	0.0 d
Cowpea (SCC)	0.0	2.7 c	0.2 ab	1.3 b
Methyl bromide (MBF)	0.0	0.5 d	0.0 b	0.0 d
Control (UC)	0.0	16.0 a	1.8 ab	3.8 a

[z]Data are untransformed arithmetic means of 6 replications. Means in each column followed by the same letter do not differ at $P \leq 0.05$, according to Waller-Duncan test performed on log-transformed data.

ment both had the lowest ($P \leq 0.05$) number of ring nematodes per 100 cm^3 soil relative to the other treatments (Table 1). No root-knot nematodes (*Meloidogyne* spp.) were detected in any treatment, however, numbers are often below detectable levels following a non-cropped summer season in Florida (McSorley and Pohronezny, 1981).

At the end of the 2003 experiment, MBF and CCSRB treatments had lower numbers of ($P \leq 0.05$) root-knot nematode juveniles in soil than all other treatments (Table 2). Similarly, the MBF treatment contained fewer ($P \leq 0.05$) ring nematodes than all other treatments, but all other treatments reduced ($P \leq 0.05$) the numbers of ring nematodes as compared to the control. No treatment effects were observed on the minimal populations of other nematodes found, including spiral, stubby root, and lesion nematodes.

2004: At planting, no differences were observed among the population densities of root-knot, ring, or stubby-root nematodes (Table 3). At termination of the pepper crop, the CCSRB and SRB treatments were as effective as MBF at managing root-knot and ring nematodes, respectively (Table 4).

Table 2. Effect of soil treatments on plant-parasitic nematode numbers in January 2004.

	Nematodes per 100 cm^3 soil			
Treatment	Root-knot	Ring	Stubby-root	Lesion
Solarization (SRB)	55.5 a[z]	2.8 b	0.1	0.3
Solarization + cowpea (CCSRB)	13.2 b	1.8 b	0.0	0.0
Flat solarization (SFS)	169.7 a	2.3 b	0.0	0.0
Cowpea (SCC)	75.7 a	1.5 b	0.0	0.1
Methyl bromide (MBF)	0.8 b	0.2 c	0.0	0.0
Control (UC)	180.5 a	6.6 a	0.0	0.1

[z]Data are untransformed arithmetic means of 6 replications. Means in each column followed by the same letter do not differ at $P \leq 0.05$, according to Waller-Duncan test performed on log-transformed data.

Table 3. Effect of soil treatments on plant-parasitic nematode numbers in August 2004.

	Nematodes per 100 cm^3 soil		
Treatment	Root-knot	Ring	Stubby-root
Solarization (SRB)	1.2	4.5 ab[z]	1.3
Solarization + cowpea (CCSRB)	0.0	0.7 ab	1.3
Flat solarization (SFS)	0.2	3.3 ab	0.3
Cowpea (SCC)	0.0	0.5 ab	0.7
Methyl bromide (MBF)	0.0	0.0 b	0.0
Control (UC)	0.7	3.3 a	0.2

[z]Data are untransformed arithmetic means of 6 replications. Means in each column followed by the same letter do not differ at $P \leq 0.05$, according to Waller-Duncan test performed on log-transformed data.

Weeds and Cutworms

2003: Prior to planting and application of MBF, the total amount of weed coverage in the three solarization treatments and the cowpea treatment was lower ($P \leq 0.05$) than the MBF and UC treatments. Plot area covered by weeds was relatively high according to the Horsfall-Barrett rating (8.33) in MBF and UC treatments (Table 5). Bahiagrass (*Paspalum notatum* L.) was the primary weed accounting for most of the coverage in the UC and MBF treatments (Table 5). Other common weeds were crabgrass (*Digitaria* spp.), hairy indigo (*Indigofera hirsuta* L.), and nutsedge (*Cyperus* spp.). Cutworm damage showed no treatment effect ($P \leq 0.05$) on transplant mortality, but data were highly variable, with the highest rate of mortality in one of the MBF plots (Table 6).

2004: Weed data were not collected prior to planting because herbicide and roto-tilling was used during the summer to minimize weed pressure prior to planting. There were no differences among treatments in the number of weeds per plot during the season (data not shown).

Table 4. Effect of soil treatments on plant-parasitic nematode numbers in December 2004.

	Nematodes per 100 cm^3 soil			
Treatment	Root-knot	Ring	Cyst	Stubby-root
Solarization (SRB)	31.7 ab[z]	0.7 bc	0.3 ab	0.2
Solarization + cowpea (CCSRB)	7.1 dc	1.1 b	0.0 b	0.0
Flat solarization (SFS)	16.3 bc	1.3 b	0.0 b	0.0
Cowpea (SCC)	18.9 bc	0.7 b	0.0 b	0.8
Methyl bromide (MBF)	0.4 d	0.0 c	0.0 b	0.0
Control (UC)	122.3 a	4.2 a	0.8 a	0.3

[z]Data are untransformed arithmetic means of 6 replications. Means in each column followed by the same letter do not differ at $P \leq 0.05$, according to Waller-Duncan test performed on log-transformed data.

Table 5. Effect of treatment on coverage of plots by weeds in August 2003.

	Horsfall-Barrett Rating[y]				
Treatment	Bahiagrass	Crabgrass	Hairy Indigo	Nutsedge	Total weeds
Solarization (SRB)	1.0 b[z]	1.0 c	1.0 c	1.3	1.5 dc
Solarization + cowpea (CCSRB)	1.0 b	1.0 c	1.0 c	1.2	1.2 d
Flat solarization (SFS)	1.0 b	1.2 bc	1.0 c	1.3	1.8 c
Cowpea (SCC)	1.2 b	2.3 a	4.5 a	1.5	6.0 b
Methyl bromide (MBF)	7.3 a	2.5 a	4.0 a	1.5	8.3 a
Control (UC)	7.7 a	2.2 ab	3.3 b	2.0	8.3 a

[y]Rating on a scale from 1 (0% of area covered with weeds) to 12 (100% of area covered by weeds). See text for complete rating scale.

[z]Data are means of 6 replications. Means in each column followed by the same letter do not differ at $P \leq 0.05$, according to Waller-Duncan test.

Yield

2003: In December of 2003 when data from all three harvests were combined, SRB and CCSRB treatments had higher total fruit weights ($P \leq 0.05$) than the MBF treatment (Table 7). The weight of U.S. Fancy grade peppers was also higher ($P \leq 0.05$) in the SRB treatment compared to the MBF treatment. Unexpectedly, the MBF treatment resulted in similar yields (total weights and numbers) to the UC treatment (Table 7).

2004: Fewer treatment effects on pepper yield were observed at the end of the 2004 experiment than in the previous season due to the occurrence of two hurricanes and a *Pythium* epidemic. There were no differences in total fruit weight among the treatments (Table 8); however, the total number of fruit in the SFS treatment was greater ($P \leq 0.05$) than in the MBF treatment. Additionally the weight of U.S. No. 1 grade peppers in the SFS treatment was greater than in the MBF treatment (Table 8).

Table 6. Effect of soil treatments on mortality of pepper transplants caused by cutworms, September and October 2003.

	23 Sept. 2003		7 Oct. 2003	
Treatment	No. dead plants per plot	Percent dead plants	No. dead plants per plot	Percent dead plants
Solarization (SRB)	0.2	0.5	0.1	0.2
Solarization + cowpeas (CCSRB)	0.3	0.7	0.2	0.4
Flat solarization (SFS)	0.8	2.3	0.1	0.2
Cowpeas (SCC)	0.2	0.5	0.1	0.2
Methyl bromide (MBF)	1.5	4.0	0.5	1.3
Control (UC)	0.7	1.8	0.3	0.9

Table 7. Effect of soil treatments on total pepper harvest by treatment in fall 2003 (three harvest dates combined).

Treatment	Fancy wt. (kg)[y]	Fancy number	US #1 wt. (kg)	US #1 number	US #2 wt. (kg)	US #2 number	Total wt. (kg)	Total number
Solarization (SRB)	11.4 a[z]	54.9 a	6.9	43.3	1.5	13.0 ab	20.3 a	112.7 a
Solarization + cowpeas (CCSRB)	10.9 ab	52.9 ab	6.9	43.3	1.5	13.8 a	19.5 ab	110.6 a
Flat solarization (SFS)	9.6 bc	46.4 bc	6.9	43.8	1.2	11.0 ab	17.8 bc	101.4 ab
Cowpeas (SCC)	9.4 c	44.4 c	7.3	46.7	1.3	10.5 ab	18.2 bc	102.8 ab
Methyl bromide (MBF)	8.5 c	43.1 c	6.8	43.8	1.7	14.7 a	17.3 c	102.7 ab
Control (UC)	9.3 c	45.8 bc	6.9	43.3	1.1	8.9 b	17.4 c	98.5 b

[y]Based on 40 plants per plot harvested; Fancy grade = minimum diameter 7.62 cm; US #1 grade = minimum diameter 6.35 cm; US #2 grade = no size minimum.
[z]Data are means of 6 replications. Means in each column followed by the same letter do not differ at $P \leq 0.05$, according to Waller-Duncan test.

DISCUSSION

The MBF and CCSRB treatments were most effective for suppressing root-knot nematodes in both years. The undetectable level of root-knot nematodes at termination of the summer treatments prior to planting in both years was expected. This is often observed following a non-cropped summer season in Florida when most root-knot nematodes are in egg stage, which are often undetectable by typical soil extraction methods (McSorley and Pohronezny, 1981). However, these undetectable populations at planting can build up to high levels on susceptible vegetable crops.

Although cowpea and solarization treatments alone were not as effective as

Table 8. Effect of soil treatments on total pepper harvest by treatment and grade in fall 2004 (three harvest dates combined).

Treatment	Fancy wt. (kg)[y]	Fancy number	US #1 wt. (kg)	US #1 number	US #2 wt. (kg)	US #2 number	Total wt. (kg)	Total number
Solarization (SRB)	2.9	14.8	2.6 ab[z]	17.3 ab	1.2 ab	13.3 abc	8.3	53.3 ab
Solarization + cowpeas (CCSRB)	3.0	14.3	2.4 ab	15.5 ab	0.9 bc	12.6 bc	7.8	49.8 ab
Flat solarization SFS)	3.1	15.3	2.9 a	19.0 a	1.3 ab	16.8 ab	10.0	64.3 a
Cowpeas (SCC)	3.0	14.3	2.2 ab	14.3 ab	0.7 c	10.2 c	8.0	49.2 ab
Methyl bromide (MBF)	2.9	14.3	1.7 b	11.7 b	0.9 bc	12.1 bc	7.4	47.0 b
Control (UC)	2.3	11.8	2.6 ab	16.9 ab	1.4 a	18.0 a	7.7	54.8 ab

[y]Based on 60 plants per plot harvested; Fancy grade = minimum diameter 7.62 cm; US #1 grade = minimum diameter 6.35 cm; US #2 grade = no size minimum.
[z]Data are means of 6 replications. Means in each column followed by the same letter do not differ at $P \leq 0.05$, according to Waller-Duncan test.

MBF, the combination of cowpea and solarization was as effective as the MBF treatment ($P \leq 0.05$) for the suppression of root-knot nematodes. Efforts have been made to combine solarization with cabbage residues or other plant materials as amendments to achieve a biofumigation effect (Gamliel and Stapleton, 1993; McGovern and McSorley, 1997). With a nematode suppressive cover crop such as 'Iron Clay' cowpea, several mechanisms could be involved including a non-host effect from the cover crop (Wang *et al.*, 2003) or enhancement of nematode natural enemies (Wang *et al.*, 2006).

Although ring nematode population densities were relatively low throughout the two seasons, significant suppression of ring nematodes by all three solarization treatments was observed at three sampling dates. Lack of treatment effects on early-season ring nematode populations in the second season may have been due to the improved management of off-season weeds in 2004, since grasses are good hosts for ring nematodes.

Sufficient weed suppression by solarization in 2003 is consistent with previous studies (McSorley *et al.*, 2004; Chase *et al.*, 1999); however, differences among the solarization treatments for weed suppression occurred. The SFS treatment did not suppress total weeds as well as the SRB and CCSRB treatments in 2003. Theoretically, flat solarization should be more effective than bedded solarization since flat solarization avoids the bed shoulder being shaded part of the day, as is the case with bedded solarization (McGovern *et al.*, 2004). Flat solarization heats the entire bed evenly, and soil contamination from poorly solarized edges is minimized. However, the flat solarization plastic was installed by hand, so the plastic was not as tight as in the raised bedded solarization that was installed with a tractor. When the plastic is loose, the heat transfer to the soil is less efficient. In addition, the plastic used for the SFS was thicker than that used for the SRB treatments, thus allowing for even more heat transfer in the SRB since thinner plastic is more efficient for solar heating of the soil (Katan, 1981; McGovern and McSorley, 1997).

Poor weed suppression by MBF in the 2003 experiment was due to lack of weed management in the summer prior to the MBF treatment. Earlier management via tillage, as done in the second season, could have avoided the problem. Not allowing the weed debris to decompose sufficiently may have interfered with fumigant efficacy because conditions were not optimal for fumigant application (Rhoades *et al.*, 1966). This in turn, likely resulted in loss of plants to cutworms, mainly in one of the MBF plots. The non-decomposed weed debris still in the soil under plastic may establish safe zones for the cutworms to hide and avoid being killed by the fumigant (Rhoades *et al.*, 1966). The heavy weed pressure and cutworm damage particularly in the MBF ultimately led to unexpected low yields, and may have accounted for the lower yield in the MBF relative to the solar bedded plots in 2003.

Growers favor soil fumigation over soil solarization because they can fumigate at the end of the summer season, killing existing weeds and reducing soilborne pest populations for the fall vegetable season; whereas solarization requires field management during the off-season. However, our results from 2003 show that this approach with fumigation alone was not practical in sites with heavy weed pressure where active weed management during the off-season is required to prepare for optimal fumigant application.

In 2003, SRB and CCSRB produced the highest yields among all the treatments. It was anticipated that the MBF would be as effective, if not more effective, as the solarization treatments; however, as previously mentioned, the excessive weeds in the MBF greatly reduced the average total yield for that treatment. The results from the SRB and the CCSRB treatments show promise, and further comparisons with other soil management techniques may be beneficial.

In 2004, the pepper yields in all treatments were less than those in 2003. This was due to flooding associated with two hurricanes and a *Pythium* epidemic (Saha *et al.*, 2006). There were no differences in yields despite differences in root-knot nematode numbers, indicating that any nematode effects were small relative to the damage caused by flooding and *Pythium*. However, the value of peppers in 2004 was much higher than in 2003 due to the shortage caused by the hurricanes. Terminal market prices for Atlanta per 12.7-kg (1 1/9 bushel) carton ranged from $35 to $45 in the third and fourth weeks of November in 2004 (USDA, 2006). The same carton price during the third and fourth weeks of November in 2003 only ranged from $9 to $15. Therefore, total profits remained the same despite the hurricanes. Even with the significantly lower yields in 2004, it was possible to make more profit since the prices were more than twice those of 2003, and the yields were 50% below those of 2003.

In conclusion, the CCSRB treatment was comparable to the performance of MBF for root-knot nematode suppression. All solarization methods were effective in suppressing weeds compared to the weed fallow control. While the effect of solarization on pepper yield was not consistent, cost for solarization was three times less than that for the MBF (U.S. EPA, 2006). Additional cost of cowpea seeds and management also affect the cost of production. Further research is needed for solarization and cover cropping treatments to broaden the pest suppression spectrum beyond nematodes and weeds to include other soil-borne pathogens.

ACKNOWLEDGMENTS

The authors would like to thank J. J. Frederick, Elio Jovicich, and P. Jackson for their technical assistance and for reviewing the manuscript. This work was supported in part by USDA, CSREES grant no. 2002-51102-01927. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture or the University of Florida.

LITERATURE CITED

Chase, C. A., T. R. Sinclair, and S. T. Locascio. 1999. Effects of soil temperature and tuber depth on nutsedge (*Cyperus* spp.) control by soil solarization. Weed Science 47:467-472.

Chellemi, D. O., J. Mirusso, and J. Nance. 2004. Evaluation of methyl bromide alternatives on commercial vegetable farms. Pp. 40-1 – 40-5. *In*: Proceedings of the Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. G. L. Obenauf, Ed. Methyl Bromide Alternatives Outreach, Fresno, CA.

Chellemi, D. O., S. M. Olsen, D. J. Mitchell, and R. McSorley. 1993. Reduction of phytoparasitic nematodes on tomato by soil solarization and genotype. Supplement to the Journal of Nematology 25:800-805.

Division of Hydrologic Data Services, 2004. Summary of hydrologic conditions. St. Johns River Water Management District. http://sjr.state.fl.us/programs/plan_monitor/hydro_data/hydrorpt/pdfs/hydrocond/hrpt0409.pdf

Dover, K., K.-H. Wang, and R. McSorley. 2003. Use of solarization against soilborne pathogens and pests. Dept. Entomology and Nematology, University of Florida, Gainesville, FL. http://agroecology.ifas.ufl.edu/KDover/coverpage.htm

Gamliel, A., and J. J. Stapleton. 1993. Characterization of antifungal volatile compounds evolved from solarized soil amended with cabbage residues. Phytopathology 83:899-905.

Heald, C. M., and A. F. Robinson. 1987. Effect of soil solarization on *Rotylenchulus reniformis* in the lower Rio Grande Valley of Texas. Journal of Nematology 19:93-103.

Horsfall, J. G., and R. W. Barratt 1945. An improved grading system for measuring plant diseases. Phytopathology 35:655.

Jenkins, W. R. 1964. A rapid centrifugal-flotation technique for separating nematodes from soil. Plant Disease Reporter 48:692.

Katan, J. 1981. Solar heating (solarization) of soil for control of soilborne pests. Annual Review of Phytopathology 19:211-236.

Katan, J., and J. E. DeVay. 1991. Soil Solarization. CRC Press, Boca Raton, FL.

Louws, F. J., L. M. Ferguson, K. Ivors, J. Driver, K. Jennings, D. Milks, P. B. Shoemaker, and D. W. Monks. 2004. Efficacy of methyl bromide alternatives for verticillium and weed management in tomatoes. Pp. 43-1- 43-3. *In*: Proceedings of the Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. G.L. Obenauf, Ed. Methyl Bromide Alternatives Outreach, Fresno, CA.

McGovern, R. J., and R. McSorley.1997. Physical methods of soil sterilization for disease management including soil solarization. Pp. 283-313. *In*: Environmentally Safe Approaches to Crop Disease Control. N. A. Rechcigl and J. E. Rechcigl, Eds. CRC Lewis Publishers, Boca Raton, FL.

McGovern, R. J., R. McSorley, K.-H. Wang. 2004. Optimizing bed orientation and number of plastic layers for soil solarization in Florida soil. Soil and Crop Science Society of Florida Proceedings 66:92-95.

McSorley, R. 1998. Alternative practices for managing plant-parasitic nematodes. American Journal of Alternative Agriculture 13:98-104.

McSorley, R. and R. J. McGovern. 2000. Effects of solarization and ammonium amendments on plant-parasitic nematodes. Supplement to Journal of Nematology 32:537-541.

McSorley, R., M. Ozores-Hampton, P. A. Stansly, and J. M. Conner. 1999. Nematode management, soil fertility, and yield in organic vegetable production. Nematropica 29:205-213.

McSorley, R., and J. L. Parrado. 1986. Application of soil solarization to Rockdale soils in a subtropical environment. Nematropica 16:125-140.

McSorley, R., and K. Pohronezny. 1981. A simple bioassay as a supplement to soil extraction for detection of root knot nematodes. Proceedings of the Soil and Crop Science Society of Florida 40:121-123.

McSorley, R., K.-H. Wang, and N. Kokalis-Burelle. 2004. Impact of soil-borne pest problems on field-grown snapdragon. Proceeding of the Florida State Horticultural Society. 117:301-305.

Obenauf, G. L. 2004. Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. Methyl Bromide Alternatives Outreach, Fresno, CA.

Overman, A. J., and J. P. Jones. 1986. Soil solarization, reaction, and fumigation effects on double-cropped tomato under full-bed mulch. Proceedings of the Florida State Horticultural Society 99:315-318.

Rhoades, H. L., J. A. Winchester, and A. J. Overman. 1966. Nematode control guide for vegetable production in Florida. Bulletin 707, Institute of Food and Agriculture Sciences, University of Florida, Gainesville.

Rodriguez-Kabana, R., J. R. Akridge, and J. E. Burkett. 2004. Sodium azide for control of root-knot nematode, weeds, and soilborne disease in cantaloupe production. Pp. 49-1- 49-8. *In*: Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. G. L. Obenauf, Ed. Methyl Bromide Alternatives Outreach, Fresno, CA.

Saha, S. K., R. McSorley, K.-H. Wang, and R. J. McGovern. 2006. Impacts of extreme weather and soil management treatments on disease development of *Pythium* spp. in field grown pepper. Proceedings of the Florida State Horticultural Society 118:146-149.

Sargent, S. 2000. Handling Florida vegetables:pepper. SS-VEC-927, Florida Cooperative Extension Service. University of Florida, Gainesville. http://edis.ifas.ufl.edu/VH087.

Taylor, S. 2004. Personal Communication. Coordinator of research programs, Plant Science Research and Education Unit, IFAS. Marion Co., Florida.

Thomas, B. P., L. Law, Jr., D. L. Stankey. 1979. Soil Survey of Marion County Area, Florida. US Department of Agriculture Soil Conservation Service, Washington, D.C.

United States Department of Agriculture. 2006. Fruit and vegetable market news: Commodity report. http://marketnews.usda.gov/portal/fv.

United States Environmental Protection Agency. 2005. Ozone depletion rules and regulations: The methyl bromide phaseout. http://www.epa.gov/ozone/mbr/.

United States Environmental Protection Agency. 2006. Ozone depletion rules and regulations: Solarization for controlling soilborne pests and pathogens in field crop cultivation. http://www.epa.gov/spdpublc/mbr/casestudies/volume2/solar2.html

Wang, K.-H., R. McSorley, and R. N. Gallaher. 2003. Host status and amendment effects of cowpea on *Meloidogyne incognita* in vegetable cropping systems. Nematropica 33:215-224.

Wang, K.-H., and R. McSorley. 2004. Management of nematodes with cowpea cover crops. EDIS publication ENY-712, IFAS Extension, University of Florida. http://edis.ifas.ufl.edu/IN516.

Wang, K.-H., R. McSorley, N. Kokalis-Burelle. 2006. Effects of cover cropping, solarization, and soil fumigation on nematode communities. Plant and Soil 286:229-243.

Received: *18/X/2006* *Accepted for publication:* *19/XII/2006*

Recibido: *Aceptado para publicación:*