ANAEROBIC SOIL MANAGEMENT PRACTICES AND SOLARIZATION FOR NEMATODE CONTROL IN FLORIDA†

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ABSTRACT

Sotomayor, D., L. H. Allen, Jr., Z. Chen, D. W. Dickson, and T. Hewlett. 1999. Anaerobic soil management practices and solarization for nematode control in Florida. Nematropica 29:153-170.

Combinations of flooding, solarization, and amending soil with yard waste compost (YWC) treatments were evaluated for control of root-knot nematodes (*Meloidogyne arenaria*). Experiments were conducted at Gainesville, Florida for 12-wk periods in the summer of 1996 and 1997 in mesocosms containing an Arredondo fine-sand. Flooding soil induced anaerobic conditions with soil redox potentials near -200 mV in both years. Flooding decreased soil root-knot nematode populations in the order of: continuous ≤ intermittent < non-flooded with values (J2/100 cm^3) of 9, 10, and 36 in 1996, and of 5, 23, and 212 in 1997, respectively. The number of galls found in tomato (*Lycopersicon esculentum* c.v. Rutgers) roots as a result of both intermittent and continuous flooding in both years were < 1. Endogenous soil populations of ring (*Criconemella* spp.) and stubby-root (*Paratrichodorus* spp.) nematodes were also reduced by flooding. Average daily maximum soil temperatures in solarized plots were in the order of: non-flooded with compost > flooded continuously > and non-flooded soil treatments in 1996 and non-flooded with compost > non-flooded soil > flooded continuously in 1997. In 1996, solarization reduced root-knot nematode numbers 83% in non-flooded plots but did not reduce galling. Combinations of flooding and solarization also reduced root-knot nematode numbers in non-amended plots but galling incidence was not significantly different from the control. In 1997, solarization alone or in combination with other treatments effectively reduced soil root-knot nematode numbers. Root-knot, ring and stubby root nematode populations increased in soil amended with YWC and following rice (*Oryza sativa* L. cv. Lemont) grown during the flooding period. Combinations of continuous flooding and solarization during the warmest days of the year deserve further study as tools for nematode control under field conditions.

Key Words: flooding, methyl bromide alternatives, organic amendment, root-knot nematodes, soil management, solarization.

RESUMEN

Sotomayor, D., L. H. Allen, Jr., Z. Chen, D. W. Dickson y T. Hewlett. 1999. Prácticas de manejo anaeróbico del suelo y solarización para el control de nematodos en la Florida. Nematrópica 29:153-170.

Los efectos de tramientos sobre el suelo de enmienda orgánica (cieno sanitario con residuos vegetativos), inundación y solarización fueron evaluados para el control de *Meloidogyne arenaria.* Los experimentos se llevaron a cabo en Gainesville, Florida por períodos de 12 semanas durante el verano de 1996 y 1997 en microparcelas con suelo arenoso Arredondo. La inundación del suelo indujo condiciones anaeróbicas con un potencial redox del suelo cerca de -200 mV en ambos años. La inundación

†Florida Agricultural Experiment Station Journal Series Number R-07023.

redujo las densidades finales de *M. arenaria* en el orden ascendente de: continuamente ≤ intermitentemente < drenado, con valores de (J2/100 cm^3): 9, 10 y 36 en 1996, y de 5, 23 y 212 en 1997, respectivamente. El número de agallas encontrado en raíces de tomato (*Lycopersicon esculentum* c.v. Rutgers) como resultado de inundaciones continuas e intermitentes fueron <1, para ambos años. Las densidades de *Criconemella* spp. y *Paratrichodorus* spp. también se redujeron significativamente como resultado de la inundación. Los promedios de la temperatura máxima diaria del suelo para los tratamientos solarizados estuvieron en el orden de: drenado enmendado con composta > continuamente inundado > drenado en 1996 y drenado enmendado con composta > drenado > continuamente inundado en 1997. En 1996, la solarización redujo las densidades de *M. arenaria* en un 83% en parcelas sin inundar pero la reducción en el número de agallas no fué significativa. La combinación de inundación con solarización también redujo las densidades de *M. arenaria* en suelo sin enmendar pero el número de agallas no fue significativamente diferente del control. En 1997, la solarización utilizada sola o en combinación con otros tratamientos redujo efectivamente las densidades de *M. arenaria* en el suelo. El sembrar arroz (*Oryza sativa* L. var. Lemont) durante el período de inundación y enmendar el suelo con composta orgánica no fueron buenas alternativas ya que las densidades de *M. arenaria, Criconemella* spp. y *Paratrichodorus* spp. también aumentaron. Los resultados demuestran que la combinación de inundar el suelo por períodos de entre 6 y 12 semanas con solarización debe ser estudiado más a fondo como una herramienta para el control de nematodos en condiciones de campo.

Palabras Claves: alternativas a bromuro de metilo, enmiendas orgánicas, inundación, manejo de suelos, *Meloidogyne arenaria,* solarización.

INTRODUCTION

Soil fumigation with methyl bromide is widely practiced in the USA for pre-plant control of nematodes, weeds, and plant pathogens on high value crops. Soil fumigation accounts for about 80% of the manufactured material (Taylor, 1994). The treatment of agricultural soils with methyl bromide has been suggested to be a significant source of atmospheric methyl bromide which is involved in stratospheric ozone loss (Cicerone, 1994; Yagi *et al.*, 1995). Public awareness of environmental risks associated with pesticides, especially methyl bromide, has resulted in increased interest in finding biological and cultural methods for pest management. In addition, methyl bromide is scheduled for phase out by the year 2005.

Fumigated vegetable production (especially tomato) in Florida is done in sandy soils with shallow water tables which must be drained for crop production to prevent anoxic soil conditions. High rainfall usually occurs in summer, and during this period the fields are either fallowed, cover cropped, or managed at a low scale. Based on soil classification, we estimated that water table/flooding strategies for pest management could be employed in about 20% of the Floridan land surface (Buol, 1973). Brown (1933) and Thames and Stoner (1953) demonstrated that flooding organic soils was an effective strategy for nematode control. Rhoades (1964) reported that both flooding and fallowing decreased root-knot nematode densities; however, if a natural weed population was present, root-knot nematode populations increased. Nematode control by flooding organic soils has been reviewed by Watson (1921) and Good (1987) and it appears that conditions which decrease soil aeration also decrease the activity of nematodes (Duncan, 1991). Flooding has not been investigated for nematode control in sandy soils.

Municipal solid yard waste compost (mixture of yard trimmings with biosolids and other biodegradable materials; YWC) has been utilized in commercial vegetable production systems primarily for improvement of soil physical and chemical properties (Gallaher and McSorley, 1996). Compost can also reduce the incidence of some soilborne plant pathogens (McSorley and Gallaher, 1995) and weeds (Roe *et al.*, 1993). Biocidal agents toxic to nematodes were released from the decomposition of organic amendments (Dunn, 1994). In addition, nematode antagonistic microorganisms were stimulated by the addition of organic amendments such as chicken litter (Riegel *et al.*, 1996) and pine bark (Chavarria-Carvajal *et al.*, 1998), with an associated decrease in nematode population densities related to the amount of added organic matter.

Soil solarization for nematode control has been investigated in a number of crops and locations characterized by hot, clear weather (McSorley and Parrado, 1986; Chellemi *et al.* 1993). Overman (1985) reported that tomato yields were highest with solarization when compared to other preseason management treatments in central Florida. In northern Florida, Chellemi *et al.* (1993, 1994), reported that nematodes and other soilborne pathogens were reduced by summertime solarization treatments. In Florida during late spring and summer, solar radiation appears to be sufficient even with substantial cloudiness, if the energy is effectively absorbed, distributed, and retained in the soil. Solarization efficacy may be improved with certain plastics such as thermal infrared-trapping plastic mulch (Chase *et al.*, 1997), adequate soil water content, and darker soil color as a result of adding organic amendments to sandy Florida soils (Ham *et al.*, 1993; Jury *et al.*, 1991).

In this experiment, the effects of anaerobic conditions induced by flooding, heating by solarization, and organic amendment were investigated for control of root-knot nematode (*M. arenaria*) in mesocosms using a fine sandy soil. Rice (*Oryza sativa* L. cv. Lemont) was also tested as an alternative crop during the flooding period, because it can be grown during the Florida summer (Alvarez, 1993; Schueneman *et al.*, 1993).

MATERIALS AND METHODS

Field Site and Treatments: The experiment was conducted in 1996 and 1997 at the University of Florida, Gainesville in outdoor mesocosms (0.75 m^3 polyethylene stock-watering tanks) with a soil surface area of 1.10 m^2. The bottom of each mesocosm had a gravel layer underlain by a slit-perforated well point pipe laid horizontally across the bottom to permit drainage of water. In August 1995, mesocosms were filled to a depth of 5 to 10-cm from the top with soil alone or soil mixed with YWC. The soil material was collected from the upper 0-25 cm of an Arrendondo fine sand (loamy, siliceous, hyperthermic Grossarenic Paleudult) using a mechanical shovel and sieved through a wire screen.

In 1996, the experiment consisted of 14 treatments in an incomplete factorial arrangement (Table 1). The factors were flooding, crop, solarization, and organic amendment. In 1997, the experiment consisted of 12 treatments in a factorial arrangement with the same factors except that no crop was planted (Table 1). Two additional treatments evaluated the effect of rice grown during the flooding regime with and without an organic amendment. In both years, the experimental design was a randomized complete block with four replications.

The soil flooding treatments consisted of continuous flooding for 12 weeks, intermittent flooding for 12 weeks (5 weeks flooded, 2 weeks drained, 5 weeks flooded), and non-flooded soil. Flooding was performed by sealing the drainage hole at the bottom of the mesocosms and adding municipal tap water to a level

Table 1. Description of soil mesocosm treatments used for nematode control in 1996 and 1997.

Flood[r]	Crop[s]	Solarization[t]	Amendment[u]
Flood (C)	Fallow	Solarize	Compost[v,y,z]
Flood (C)	Fallow	Solarize	Compost (N)[z]
Flood (C)	Fallow	Solarize (N)	Compost[z]
Flood (C)	Fallow	Solarize (N)	Compost (N)[y,z]
Flood (I)	Fallow	Solarize	Compost[w]
Flood (I)	Fallow	Solarize	Compost (N)[x]
Flood (I)	Fallow	Solarize (N)	Compost[z]
Flood (I)	Fallow	Solarize (N)	Compost (N)[z]
Flood (N)	Fallow	Solarize	Compost[y]
Flood (N)	Fallow	Solarize	Compost (N)[y]
Flood (N)	Fallow	Solarize (N)	Compost[y]
Flood (N)	Fallow	Solarize (N)	Compost (N)[y]
Flood (C)	Rice[x]	Solarize (N)	Compost[z]
Flood (C)	Rice	Solarize (N)	Compost (N)[z]

[r]Flood (C) = soil flooded continuously for 12 weeks; Flood (I) = soil flooded intermittently for 12 weeks (5-flood; 2-drain; 5-flood); Flood (N) = non-flooded soil (continuously drained).
[s]Rice cv. Lemont.
[t]Solarize = soil solarization; heat and cover treatment (mesocosms covered with bubble wrap overlain by clear IR-absorbing plastic); Solarize (N) = non-solarized soil.
[u]Compost = soil amended with yard-waste compost; Compost (N) = non-composted soil.
[v]During 1996 experiment this treatment was not performed, and the treatment for this soil was: Flood (N)/Rice/Solarize (N)/Compost.
[w]During 1996 experiment this treatment was not performed, and the treatment for this soil was: Flood (C)/Fallow/Solarize/Compost (N).
[x]During 1996 experiment the treatment for this soil was: Flood (N)/Rice/Solarize (N)/Compost (N).
[y]Thermocouples were installed in these treatments in one block.
[z]Redox probes were installed in these treatments in one block.

approximately 5-cm above the soil surface. The flooding regime was accomplished over a 12 week period, from 2 August to 25 October in 1996 and from 26 June to 24 September in 1997. Plots were maintained flooded by adding water to compensate for evapotranspiration losses. The two crop factors were fallow or planted to rice. Solarization was performed by covering the top of the mesocosms with bubble wrap overlain by a 150 µm (6 mil) clear infrared-absorbing polyethylene film (Chase *et al.*, 1997). The YWC was incorporated and mixed with soil at a rate of approximately 1000 Mt/ha to a depth of 40-cm from the top of the mesocosm. The YWC was similar to that used by McSorley and Gallaher (1997), and was obtained from Enviro-Comp Services of Jacksonville, Florida.

Nematodes: Mesocosms were inoculated with second-stage juveniles (J2) of *Meloidogyne arenaria* (Neal) Chitwood race 1 on 16 May 1996. Nematodes used for inoculations originated from a greenhouse isolate maintained on tomato at the University of Florida, Gainesville. A suspension (0.5 L) of approximately 2 000 J2/ml was dispensed uniformly in pre-drilled holes in the soil. Eggplant (*Solanum melongena*) seedlings were then transplanted to the mesocosms as a host for nematode propagation. Plots were fertilized weekly with 200 kg ha^{-1} of 36-6-6 (N-P_2O_5-K_2O) commercial formulation. After two months, randomly selected eggplant root systems were evaluated for root galling and initial soil nematode population densities determined. Eggplant roots were then chopped into 3- to 5-cm long pieces and incorporated into the soil. Mesocosms were sampled 7 and 12 weeks after flooding and solarization treatments were initiated. Nine soil samples (0-20 cm deep, ≈200 cm^3/sample) per mesocosm were composited and mixed. Second-stage juveniles (J2) of *M. arenaria* were extracted from 100 cm^3 soil using a modified centrifugal flotation method (Barker, 1985). Nematodes were counted in a 5-ml aliquot using an inverted compound microscope at 40× magnification. Counts in 1997 included indigenous ring (*Criconemella* spp.) and stubby-root (*Paratrichodorus* spp.) nematodes using the same procedure.

The potential infectivity of surviving nematodes at the end of the 12-week-flooding period was evaluated by bioassay in the greenhouse. Soil from each mesocosm was added to pasteurized 15-cm diameter clay pots and a 2-leaf stage tomato (*Lycopersicon esculentum* c.v. Rutgers) seedling was transplanted. A 20-20-20 commercial fertilizer solution was applied once a week and insecticide and water added as needed. Plants were assessed for number of root galls per root system after 30 days.

In 1997, eggplant was grown in the greenhouse at 25°C and *M. arenaria* eggs were added at a rate of 8 000 eggs/plant. Galling was visible on eggplant roots prior to transplanting. The infected plants were transplanted to the mesocosms in late March at a density of 9 plants per plot. The mesocosms were irrigated and fertilized as needed during an 8-week period. Two randomly selected plants from each mesocosm were evaluated for galling and aboveground portions were cut and removed 2 weeks prior to initiation of flooding. Soils were sampled to determine J2 population densities prior to initiation of flooding (24 June 1997), after flooding (24 September, 1997), and after tomato harvest (20 November 1997).

In 1997, six tomato seedlings (cv. Florida 47) were transplanted to mesocosms after completion of flooding treatments on 3 October. Tomato biomass in plots previously planted to rice could not be compared to previously fallowed plots because harvesting rice delayed tomato transplanting. Plants were fertilized weekly and irrigated as needed. Aboveground biomass was determined 75 days after transplanting and the root system was dug from the soil and indexed for root galls using a 0-10 scale (0 = no root galls, 1 = 1-10% roots galled, 2 = 11-20% roots galled, ..., 10 = 91-100% roots galled; Barker *et al.*, 1986).

Rice: In 1996, pre-germinated rice (*Oryza sativa* L. cv. Lamont) seedlings were transplanted into flooded or non-flooded mesocosms at a density of 18 plants/mesocosm seven days after initiation of flooding. Rice planted on non-flooded soil (drained plots) were well irrigated and fertilized during the experiment (3 200 kg ha^{-1} of 16-10-10 commercial fertilizer). Aboveground rice biomass (dry wt.), number of tillers, and surviving plants were determined 95 days after transplanting. Rice roots were inspected for galling by staining with 0.15% phloxine B solution. In 1997 rice was transplanted 35 days after flooding and harvested 78 days after transplanting. Other management practices were the same as in 1996.

Purple nutsedge (*Cyperus rotundus* L.) tubers were planted in mesocosms in August 1995. Plants were allowed to proliferate in the plots prior to and during the experiment in order to evaluate treatment effects on nutsedge growth and survival. This data will be published elsewhere.

Soil Temperature and Redox Potentials: Soil temperature was monitored in eight treatments of one block to evaluate the efficacy of the solarization treatments and to determine how flooding influenced soil temperatures. Thermocouples were installed in the middle of each plot at 0, 5, 15 and 25-cm soil depths and were connected to a Campbell CRT-10 data-logger (Campbell Scientific, Inc., Logan, Utah). Sequential temperature readings were gathered every 10 min with an average value recorded every 0.5 h. Temperature data were summarized to obtain the season mean and maximum values of daily temperature maxima for each treatment where thermocouples were installed.

The soil oxidation-reduction potential was used as an indicator of the degree of anaerobiosis. Measurements were made by placing one combination oxidation-reduction potential probe (ORP, Cole Palmer, Niles, IL) to a depth of 15-cm in each of eight treatments of one block. Redox readings were collected every 10 min and average values were recorded every 0.5 h into a CRT-10 datalogger. Performance of the ORP electrodes was checked before and after inserting into the soil using a saturated quinhydrone solution buffered to pH 4.0 and pH 7.0. Electrodes with readings that differed more than ± 20 mV of expected values were not used. The measured potentials (Eh measured) were converted to potential in the system (Eh actual) relative to standard H_2 electrode by adding the calomel reference potential and correcting for temperature (°C) as follows:

$$\text{Eh(actual)} = \text{Eh(measured)} + (-0.66 \times (\text{temperature}) + 260.54)$$

Because the soil pH measurements were between 6 and 7, final redox potentials were not corrected for pH. There was excellent agreement between redox measurements obtained using temporarily inserted platinum-tip electrodes and datalogger readings.

Statistical Analysis: All attributes evaluated other than redox potential and soil temperature were subjected to analysis of variance using GLM and ANOVA procedures (SAS Institute, Cary, 1996). Treatment means were compared with Duncan's multiple-range test. The data were also analyzed with a factorial model to examine which factors and/or interactions were contributing to the observed results. Since the structure was incomplete in 1996, the analysis was divided into three parts. In the first, eight treatments without solarization were included making up a 2 × 2 × 2 factorial (flood × crop × compost). In the second, 6 treatments were selected from fallow and non-amended organic mulched plots making up a 3 × 2 factorial (flood × solarization). In the third, 4 treatments were included from fallow, non-flooded plots making up a 2 × 2 factorial (solarization × compost).

RESULTS AND DISCUSSION

Soil Redox Potentials: In 1996, soils became anaerobic within 2 days after flooding began (Fig. 1A). Soil redox potentials near -200 mV were maintained when soils were flooded. Ponnamperuma (1972) has suggested that the rate and degree of reduction are influenced by the presence of decomposable organic matter, temperature, and content of electron acceptors. Since similar patterns of soil redox potentials were observed in YWC amended and unamended treatments, this suggests that electron donor and acceptor content were very similar among the treatments (Flessa

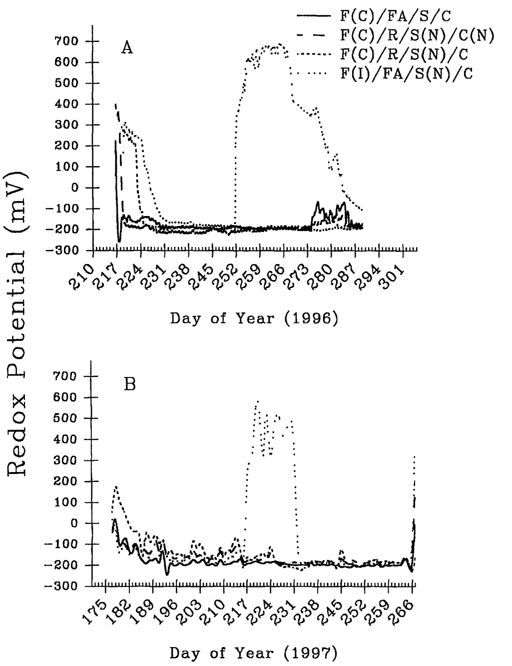

Fig. 1. Temporal variation in soil redox potentials of selected treatments during (A) 1996 and (B) 1997 experiments. Symbols for treatments are F(C) = continuous flood, F(I) = intermittent flood, S = solarize, S(N) non-solarize, FA = Fallow, R = rice, C = soil amended with compost, C(N) = non-amended soil.

and Beese, 1995; Kludze and DeLaune, 1995). It was anticipated that the mineralization of added organic material would add both additional C and energy source, contributing to an increase in the rate of reduction, but this was not observed in the experiment. Drainage (after 5 weeks) made soils aerobic, but a longer time period was needed to make soils anaerobic after re-flooding than at the start of the experiment. In 1997, initial redox measurements were low, probably because data were collected hours after flooding was initiated (Fig. 1B). It took about 10 days for lowest soil redox potentials to be achieved. As in 1996, drainage after 5 weeks of flooding made soils aerobic; however, in contrast to the previous year, re-flooding immediately lowered soil redox potential. Lower soil temperatures detected in 1996 during the re-flooding event may have influenced the intensity of reduction measured (Ponnamperuma, 1972).

Soil Temperature: Overall, higher season mean and maximum values of daily soil temperature maxima were recorded in 1997 than in 1996 in all plots at all depths because the experiment was initiated earlier in 1997 (26 June) than in 1996 (2 August). Season mean of maximum daily soil temperatures in the control treatment (Flood (N)/Solarize (N)/Compost (N)) was 42.4°C at 0 cm and 31.4°C at 25 cm in 1997, and 29.9°C at 0 cm and 28.0°C at 25 cm in 1996 (Table 2). In 1996, solarization increased daily maximum soil temperatures on average 20.0, 7.0, and 5.8°C in Flood (N)/Compost, Flood (C)/Compost (N), and Flood (N)/Compost (N) treatments, respectively at 0 cm. At 25 cm, solarization increased daily maximum soil temperatures on average 3.2, 3.6, and 2.1°C in Flood (N)/Compost, Flood (C)/Compost (N), and Flood (N)/Compost (N), respectively. Flooding increased daily maximum soil temperatures on average 1.9°C at 0 cm and 1.1°C at 25 cm in Solarize/Compost (N) treatment and were similar at both depths in Solarize (N)/Compost (N) treatment. In 1996, amending soil with YWC increased daily maximum soil temperatures on average 15.9°C at 0 cm and 1.2°C at 25 cm in Flood (N)/Solarize soil.

In 1997, solarization increased daily maximum soil temperatures on average 32.5, 8.1, and 4.9°C in Flood (N)/Compost, Flood (C)/Compost (N), and Flood (N)/Compost (N) treatments, respectively at 0 cm (Table 2). At 25 cm, solarization increased daily maximum soil temperatures on average 4.3, 3.5, and 2.5°C in Flood (N)/Compost, Flood (C)/Compost (N), and Flood (N)/Compost (N) treat-

Table 2. Seasonal mean, standard deviation (s.d.), and maximum (Max.) values of daily soil temperature maxima determined during 1996 and 1997 experiments in fallow treatments[z].

	Max.	Mean	s.d.	Max.	Mean	s.d.	Max.	Mean	s.d.
Depth (cm)	Flood (C)/Solarize/ Compost (N)			Flood (N)/Solarize/ Compost			Flood (N)/Solarize/ Compost (N)		
	1996								
0	48.0	37.6	5.7	72.6	51.6	12.3	47.1	35.7	4.9
5	44.4	35.1	4.7	54.3	39.7	6.7	42.6	33.8	4.1
15	41.3	33.4	4.0	43.7	34.9	4.4	40.1	32.6	3.6
25	36.5	31.2	3.1	36.3	31.3	3.0	34.5	30.1	2.7
	1997								
0	54.7	43.1	5.3	77.3	67.4	8.1	53.9	47.3	4.6
5	48.3	39.1	4.0	51.4	44.5	4.2	48.0	41.8	3.5
15	44.4	36.6	3.1	44.2	39.0	3.0	45.1	39.3	3.0
25	38.9	33.7	2.0	37.6	34.4	1.7	37.5	33.9	1.5
	Flood (C)/Solarize (N)/ Compost (N)			Flood (N)/Solarize (N)/ Compost			Flood (N)/Solarize (N)/ Compost (N)		
	1996								
0	42.5	30.5	3.8	48.3	31.6	4.9	39.8	29.9	3.4
5	36.8	29.3	3.1	36.4	28.9	2.9	36.1	29.0	2.9
15	35.0	28.5	2.8	32.8	28.1	2.6	34.7	28.5	2.7
25	32.5	27.6	2.6	32.3	28.1	2.6	33.0	28.0	2.6
	1997								
0	38.8	35.0	2.3	46.0	34.9	3.6	56.6	42.4	7.5
5	36.2	32.8	1.8	36.0	31.8	1.9	39.6	34.9	2.0
15	34.7	31.6	1.5	34.0	30.7	1.3	37.4	33.3	1.6
25	32.4	30.2	1.0	32.6	30.1	1.0	34.7	31.4	1.2

[z]Treatment descriptions are: Flood (C) = soil flooded continuously for 12 weeks, Flood (I) = soil flooded intermittently for 12 weeks (5-flood; 2-drain; 5-flood), Flood (N) = non-flooded soil (continuously drained), Solarize = soil solarization (mesocosms covered with bubble wrap overlain by clear IR-absorbing plastic), Solarize (N) = non-solarized soil, Compost = soil amended with yard-waste compost, Compost (N) = non-composted soil.

ments, respectively (Table 2). The mean of daily maximum soil temperatures at 0 and 25 cm were actually lower as a result of flooding in both Solarize/Compost (N) and Solarize (N)/Compost (N) treatments (Table 2). Amending soil with YWC increased soil temperature 20.1°C at 0 cm and was similar (0.5°C temperature difference) at 25 cm in Flood (N)/Solarize soil.

The higher soil temperatures due to solarization obtained in flooded non-amended soils illustrates the importance of water for proper heat conduction in soils (Katan, 1981). The thermal conductivity of a mineral soil will increase with water content to about 65% water-filled-pore-space, as films at the points of connection between particles will improve thermal contact and replace air which has about 20 times less thermal conductivity than water (Jury *et al.*, 1991). Solarization would be less effective in flooded soil relative to a well watered soil (of about 60% water-filled-pore-space), because the heat capacity will increase but the thermal conductivity will not increase greatly at high soil water content (approaching 100% water-filled-pore-space) (Mahrer *et al.*, 1984). The greater heat capacity in the flooded soil will require greater energy inputs or energy absorption to increase soil temperatures. If the solarization plastic cannot adequately trap incoming energy and outgoing soil heat, the result is a decrease in soil temperatures due to flooding. Although soil water content was not measured, it was observed that the surface soil in non-flooded plots were very dry on sporadic days in 1996, which may have caused the greater temperature difference between flooded and non-flooded plots in 1996 than in 1997.

Maximum soil temperatures for bare soil in this study in 1996 and 1997 were lower than values of 40.7 (5 cm) and 35.6°C (25 cm) reported by Chellemi *et al.* (1993). Similarly, maximum soil temperatures for solarized soil in this study in 1996 and 1997, were lower than values of 49.5 (5 cm) and 40.5°C (25 cm) reported by Chellemi *et al.* (1993). Adding YWC to this sandy Florida soil resulted in highest soil temperatures (0-15) probably due to the higher energy absorption beneath the plastic mulch due to the darker soil color (Ham *et al.*, 1993) (Table 2).

Effects on Nematodes: After the 12-week-flooding period in 1996, the Flood (N)/ Solarize/Compost treatment ranked lowest in soil root-knot nematode population density, although no significant differences were observed between this treatment and ten others, with values ranging from 5 to 59 J2/100 cm^3 soil (Table 3). In the subsequent tomato bioassay, the number of root galls in plants planted in soil which had been previously non-flooded and planted to rice had significantly higher galling incidence than 12 other treatments (Table 3). Galling was not observed in three fallow treatments: Flood (C)/Solarize/Compost (N), Flood (I)/Solarize/Compost (N), and Flood(I)/Solarize (N)/Compost (N).

In 1996, continuous flooding decreased soil root-knot nematode populations (70%) and galling (90%) as compared to non-flooded soil (Table 4). In both years, root-knot nematode populations and galling were similar due to intermittent or continuous flooding, but were significantly lower than in non-flooded soil (Table 4 and Table 5). In 1997, both intermittent or continuous flooding significantly decreased ring nematode populations relative to non-flooded soil (Table 5). After harvesting tomato in 1997, non-flooded soil had significantly higher galling index than continuous or intermittent flooding but tomato biomass (above-ground and below-ground) was highest for non-flooded soil (Table 6).

The results suggest that for nematode suppression it may be unnecessary to incur in an additional effort to flood, drain, and flood for extended periods as suggested by Good (1987). A 6- to 12-week-flooding interval may be sufficient for successful reduction of root-knot nematode populations. These results suggest that off-season flooding of sandy mineral soils can be used to control root-knot nematodes as has been documented for organic soils (Brown, 1933; Fishler and Winchester, 1964; Rhoades, 1964). However, higher plant bio-

Table 3. Root-knot juvenile (J2) populations and root galling in tomato bioassay after completion of flooding and solarization in 1996. There were no significant differences among treatments' in the initial J2 population. Means within columns followed by different letters are significantly different ($P \leq 0.05$) using Duncan's multiple range test.

	root-knot nematode	Galling
Treatment	J2/100cm^3	#/root system
1. Flood (C)/Fallow/Solarize/Compost (N)	7 c	0 b
2. Flood (C)/Fallow/Solarize (N)/Compost	15 c	10 b
3. Flood (C)/Fallow/Solarize (N)/Compost (N)	11 c	<1 b
4. Flood (C)/Rice/Solarize (N)/Compost	134 b	20 b
5. Flood (C)/Rice/Solarize (N)/Compost (N)	28 c	7 b
6. Flood (I)/Fallow/Solarize/Compost (N)	14 c	0 b
7. Flood (I)/Fallow/Solarize (N)/Compost	21 c	1 b
8. Flood (I)/Fallow/Solarize (N)/Compost (N)	6 c	0 b
9. Flood (N)/Fallow/Solarize/Compost	5 c	5 b
10. Flood (N)/Fallow/Solarize/Compost (N)	14 c	24 b
11. Flood (N)/Fallow/Solarize (N)/Compost	53 c	39 b
12. Flood (N)/Fallow/Solarize (N)/Compost (N)	59 c	5 b
13. Flood (N)/Rice/Solarize (N)/Compost	258 a	144 b
14. Flood (N)/Rice/Solarize (N)/Compost (N)	263 a	161 a

'Treatment descriptions are: Flood (C) = soil flooded continuously for 12 weeks, Flood (I) = soil flooded intermittently for 12 weeks (5-flood; 2-drain; 5-flood), Flood (N) = non-flooded soil (continuously drained), Rice = cv. Lemont, Fallow = soil fallowed, Solarize = soil solarization (mesocosms covered with bubble wrap overlain by clear IR-absorbing plastic), Solarize (N) = non-solarized soil, Compost = soil amended with yard-waste compost, Compost (N) = non-composted soil.

mass in non-flooded compared to flooded soils demonstrates a need to evaluate the effect of flooding on fruit yield in this crop.

The primary mode of nematode control by soil flooding is widely believed to be by asphyxiation. Juveniles as well as eggs of *Meloidogyne* spp. in soil have been found to not survive more than 10 days at a saturation moisture content, although they may survive for longer time periods when protected by unrotted plant material in a waterlogged soil-water system (Peacock, 1957). Stolzy *et al.* (1960) studied oxygen concentration effects (21 to 0%) on *M. incognita* and found that in the absence of carbon dioxide nematodes can survive for up to 10 days. Chemicals such as butyric and propionic acids, hydrogen sulfide, and perhaps others usually develop in flooded soils containing high amounts of organic matter, and could be lethal to nematodes (Hollis and Rodriguez-Kabana, 1966; Good, 1987). Sufficient information has not been gathered yet to disprove the suggestion by Van Gundy and Stolzy (1961) that nematodes can become quiescent and not necessarily killed. Furthermore, nematodes may not be equally susceptible at all stages of their life cycle or in all soil environ-ments.

Table 4. Treatment effects on soil root-knot nematode populations and root galling in tomato bioassay after completion of flooding and solarization in 1996[z]. Means followed by different letters within each effect are significantly different ($P \leq 0.05$) using Duncan's multiple range test for main effects and protected Fisher's LSD for interactions. Amendment main effects or interactions were not significant and are not reported.

		Juveniles	Galling
Source	Level	root-knot nematode (J2/100 cm^3)	# galls/root system
	-------------------- 2 × 2 × 2 factorial (flood × crop × amendment) --------------------		
Flood	Flood (N)	158 a	87 a
	Flood (C)	47 b	9 b
Crop	Rice	171 a	83 a
	Fallow	34 b	14 b
Flood × Crop	Flood (N) × Rice	260 a	152 a
	Flood (N) × Fallow	56 a	22 b
	Flood (C) × Rice	81 a	14 b
	Flood (C) × Fallow	13 a	5 b
	----------------------- 3 × 2 factorial (flood × solarization) -----------------------		
Flood	Flood (N)	36 a	15 a
	Flood (I)	10 b	0 b
	Flood (C)	9 b	0 b
Solarization	Solarize	25 a	8 a
	Solarize (N)	11 a	2 b
Flood × Solarization	Flood (N) × Solarize (N)	59 a	5 b
	Flood (N) × Solarize	14 b	24 a
	Flood (I) × Solarize	14 b	0 b
	Flood (C) × Solarize (N)	11 b	<1 b
	Flood (C) × Solarize	7 b	0 b
	Flood (I) × Solarize (N)	6 b	0 b
	-------------------- 2 × 2 factorial (solarization × amendment) --------------------		
Solarization	Solarize (N)	56 a	22 a
	Solarize	9 b	14 a

[z]Treatment descriptions are: Flood (C) = soil flooded continuously for 12 weeks, Flood (I) = soil flooded intermittently for 12 weeks (5-flood; 2-drain; 5-flood), Flood (N) = non-flooded soil (continuously drained), Rice = cv. Lemont, Fallow = soil fallowed, Solarize = soil solarization (mesocosms covered with bubble wrap overlain by clear IR-absorbing plastic), Solarize (N) = non-solarized soil, Compost = soil amended with yard-waste compost, Compost (N) = non-composted soil.

Solarization in 1996 reduced root-knot nematode densities from 56 to 9 J2/100cm^3 in fallow non-flooded plots but did not affect galling incidence (Table 4). In 1997, solarization reduced galling and nematode (root-knot and stubby-root nematode) populations and increased tomato biomass (Table 5 and Table 6). Our data confirm the results by Overman (1985) who observed that fewer nematodes were recovered from solarized soil, but that eradication of root-knot nematode populations

Table 5. Treatment effects on soil root-knot nematode, ring nematode, and stubby-root nematode populations after completion of flooding and solarization in 1997. Twelve treatments[z] in fallow soil are included making up a 3 × 2 × 2 factorial (flood × solarize × amendment). Means followed by different letters within each effect are significantly different ($P \leq 0.05$) using Duncan's multiple range test for main effects and protected Fisher's LSD for interactions.

Source	Level	Root-knot nematode (J2/100 cm^3)	Ring nematodes per 100 cm^3	Stubby-root nematodes per 100 cm^3
Flood	Flood (N)	212 a	276 A	3 a
	Flood (I)	23 b	53 B	16 a
	Flood (C)	5 b	28 B	10 a
Solarize	Solarize (N)	156 a	135 a	18 a
	Solarize	4 b	103 a	1 b
Amendment	Compost	131 a	148 a	10 a
	Compost (N)	28 b	90 b	9 a
Flood × Solarize	Flood (N) × Solarize (N)	417 a	314 a	2 a
	Flood (N) × Solarize	6 b	238 a	3 a
	Flood (I) × Solarize (N)	8 b	50 a	31 a
	Flood (I) × Solarize	1 b	55 a	<1 a
	Flood (C) × Solarize (N)	42 b	40 a	20 a
	Flood (C) × Solarize	3 b	16 a	<1 a
Flood × Amendment	Flood (N) × Compost (N)	58 b	189 b	1 a
	Flood (N) × Compost	366 a	363 a	4 a
	Flood (I) × Compost (N)	2 b	69 c	19 a
	Flood (I) × Compost	7 b	37 c	11 a
	Flood (C) × Compost(N)	25 b	12 c	6 a
	Flood (C) × Compost	20 b	44 c	15 a
Amendment × Solarize	Compost (N) × Solarize (N)	54 b	71 b	17 a
	Compost (N) × Solarize	2 b	108 b	18 a
	Compost × Solarize (N)	257 a	198 a	1 a
	Compost × Solarize	5 b	97 b	2 a
Flood × Solarize × Amendment	Flood (N) × Solarize (N) × Compost (N)	109 b	140 c	2 a
	Flood (N) × Solarize (N) × Compost	725 a	488 a	2 a
	Flood (N) × Solarize × Compost (N)	6 b	238 b	1.0 a
	Flood (N) × Solarize × Compost	8 b	238 b	6 a

[z]Treatment descriptions are: Flood (C) = soil flooded continuously for 12 weeks, Flood (I) = soil flooded intermittently for 12 weeks (5-flood; 2-drain; 5-flood), Flood (N) = non-flooded soil (continuously drained), Solarize = soil solarization (mesocosms covered with bubble wrap overlain by clear IR-absorbing plastic), Solarize (N) = non-solarized soil, Compost = soil amended with yard-waste compost, Compost (N) = non-composted soil.

Table 5. (Continued) Treatment effects on soil root-knot nematode, ring nematode, and stubby-root nematode populations after completion of flooding and solarization in 1997. Twelve treatments[z] in fallow soil are included making up a 3 × 2 × 2 factorial (flood × solarize × amendment). Means followed by different letters within each effect are significantly different ($P \leq 0.05$) using Duncan's multiple range test for main effects and protected Fisher's LSD for interactions.

Source	Level	Root-knot nematode (J2/100 cm^3)	Ring nematodes per 100 cm^3	Stubby-root nematodes per 100 cm^3
	Flood (I) × Solarize (N) × Compost (N)	4 b	52 de	39 a
	Flood (I) × Solarize (N) × Compost	12 b	48 de	22 a
	Flood (I) × Solarize × Compost (N)	<1 b	85 de	<1 a
	Flood (I) × Solarize × Compost	2 b	25 de	<1 a
	Flood (C) × Solarize (N) × Compost (N)	49 b	22 de	10 a
	Flood (C) × Solarize (N) × Compost	34 b	60 cd	30 a
	Flood (C) × Solarize × Compost (N)	1 b	3 e	1 a
	Flood (C) × Solarize × Compost	6 b	30 de	<1 a

[z]Treatment descriptions are: Flood (C) = soil flooded continuously for 12 weeks, Flood (I) = soil flooded intermittently for 12 weeks (5-flood; 2-drain; 5-flood), Flood (N) = non-flooded soil (continuously drained), Solarize = soil solarization (mesocosms covered with bubble wrap overlain by clear IR-absorbing plastic), Solarize (N) = non-solarized soil, Compost = soil amended with yard-waste compost, Compost (N) = non-composted soil.

did not occur. Maximum temperatures in solarized soil for both years ranged from 40.1 to 45.1°C at 15 cm; which is within the range of reported threshold temperatures for achieving significant reduction in root-knot nematode populations (Chellemi *et al.*, 1993; McSorley and Parrado, 1986).

In 1996, any combination of flooding and solarization reduced root-knot nematode numbers in non-amended plots but galling incidence was not significantly different from the control (Flood (N) × Solarize (N)) treatment (Table 4). In 1997, root-knot nematode numbers and galling incidence were clearly reduced due to solarization alone or any flooding × solarization combinations (Table 5 and Table 6). In 1997, stubby-root nematode populations were reduced as a result of solarization but were not affected by any of the other factors or their interactions (Table 5). Any flooding and solarization combination significantly reduced the galling incidence relative to control (non-flooded, non-solarize) but did not influence tomato biomass (Table 6).

Root-knot nematode populations and galling in the tomato bioassay were higher in 1996 in treatments where rice was planted compared to fallow (Table 4). Galling incidence was highest in the non-flooded, rice treatment and similar values were obtained (5 to 22 galls/root system) in the other Flood × Crop treatment combinations. Immediately after flooding in 1997, root-knot, ring and stubby-root nematode numbers increased in soil previously planted to rice (Table 7) but tomato biomass was not significantly influenced by planting rice.

In 1996, flooding increased ($P \leq 0.05$) the number of rice tillers per plant (15 versus 6), number of panicles per plant (16 versus 4), and total aboveground biomass

Table 6. Treatment effects on tomato root galling, aboveground and root biomass in tomato crop gown in mesocosm following flooding and solarization in 1997. Twelve treatments[z] in fallow soil are included making up a 3 × 2 × 2 factorial (flood × solarize × amendment). Means followed by different letters within each effect are significantly different ($P \leq 0.05$) using Duncan's multiple range test for main effects and protected Fisher's LSD for interactions.

Source	Level	Galling index Scale (0-10)	Tomato biomass (g dry wt./plot)	
			Aboveground	Roots
Flood	Flood (N)	4 a	94.9 a	20.2 a
	Flood (I)	<1 b	78.1 b	15.1 b
	Flood (C)	<1 b	72.3 b	17.8 ab
Solarize	Solarize (N)	2 a	51.2 b	11.0 b
	Solarize	1 b	112.0 a	24.3 a
Amendment	Compost	2 a	108.1 a	14.5 b
	Compost (N)	1 a	55.4 b	20.8 a
Flood × Solarize	Flood (N) × Solarize (N)	6 a	60.5 a	13.8 a
	Flood (N) × Solarize	2 b	129.0 a	26.5 a
	Flood (I) × Solarize (N)	<1 c	43.4 a	9.5 a
	Flood (I) × Solarize	<1 c	112.0 a	20.9 a
	Flood (C) × Solarize (N)	<1 c	49.9 a	9.7 a
	Flood (C) × Solarize	<1 c	94.7 a	25.8 a
Flood × Amendment	Flood (N) × Compost (N)	4 a	70.0 a	17.0 a
	Flood (N) × Compost	4 a	119.8 a	23.3 a
	Flood (I) × Compost (N)	<1 a	43.8 a	11.5 a
	Flood (I) × Compost	<1 a	112.5 a	18.7 a
	Flood (C) × Compost (N)	<1 a	52.6 a	15.0 a
	Flood (C) × Compost	<1 a	92.0 a	20.5 a
Amendment × Solarize	Compost (N) × Solarize (N)	2 a	38.4 c	11.0 c
	Compost (N) × Solarize	2 a	72.5 b	11.0 c
	Compost × Solarize (N)	1 a	64.1 b	18.0 b
	Compost × Solarize	<1 a	152.0 a	30.7 a
Flood × Solarize × Amendment	Flood (N) × Solarize (N) × Compost (N)	6 a	47.3 fg	14.0 a
	Flood (N) × Solarize (N) × Compost	6 a	73.8 de	13.7 a
	Flood (N) × Solarize × Compost(N)	3 a	92.0 cd	20.0 a
	Flood (N) × Solarize × Compost	2 a	165.0 ab	33.0 a

[z]Treatment descriptions are: Flood (C) = soil flooded continuously for 12 weeks, Flood (I) = soil flooded intermittently (I) for 12 weeks (5-flood; 2-drain; 5-flood), Flood (N) = non-flooded soil (continuously drained), Solarize = soil solarization (mesocosms covered with bubble wrap overlain by clear IR-absorbing plastic), Solarize (N) = non-solarized soil, Compost = soil amended with yard-waste compost, Compost (N) = non-composted soil.

Table 6. (Continued) Treatment effects on tomato root galling, aboveground and root biomass in tomato crop gown in mesocosm following flooding and solarization in 1997. Twelve treatments[z] in fallow soil are included making up a 3 × 2 × 2 factorial (flood × solarize × amendment). Means followed by different letters within each effect are significantly different ($P \leq 0.05$) using Duncan's multiple range test for main effects and protected Fisher's LSD for interactions.

Source	Level	Galling index Scale (0-10)	Tomato biomass (g dry wt./plot)	
			Aboveground	Roots
	Flood (I) × Solarize (N) × Compost (N)	1 a	37.8 g	10.3 a
	Flood (I) × Solarize (N) × Compost	<1 a	49.0 efg	8.7 a
	Flood (I) × Solarize × Compost (N)	<1 a	49.8 efg	12.7 a
	Flood (I) × Solarize × Compost	<1 a	176.0 a	28.7 a
	Flood (C) × Solarize (N) × Compost (N)	<1 a	30.3 g	8.7 a
	Flood (C) × Solarize (N) × Compost	<1 a	69.5 def	10.7 a
	Flood (C) × Solarize × Compost (N)	<1 a	75.0 de	21.3 a
	Flood (C) × Solarize × Compost	<1 a	114.0 bc	30.3 a

[z]Treatment descriptions are: Flood (C) = soil flooded continuously for 12 weeks, Flood (I) = soil flooded intermittently (I) for 12 weeks (5-flood; 2-drain; 5-flood), Flood (N) = non-flooded soil (continuously drained), Solarize = soil solarization (mesocosms covered with bubble wrap overlain by clear IR-absorbing plastic), Solarize (N) = non-solarized soil, Compost = soil amended with yard-waste compost, Compost (N) = non-composted soil.

(669 versus 77 g dry wt./plot). The increased growth of rice under flooded conditions is probably not due solely due to improved soil fertility (as only Mehlich 1 extractable Ca and P increased under flooded conditions, data not shown) but rather to the inability of root-knot nematodes to induce galling under flooded conditions. Bridge and Page (1982) have shown that adequate nutrient absorption by rice roots occurs from flood waters even when root-knot nematodes have invaded the root system. Other studies have shown rice cultivars to be susceptible to some species of root-knot nematode (Thames and Stoner, 1953; Bridge and Page, 1982) and the cultivar tested in this study is a host to root-knot nematode so that it should not be used as an off-season cash crop, even under flooded conditions. It appears that root-knot nematode can invade rice roots during flooded and non-flooded regimes maintaining their potential to infect a subsequent susceptible crop.

Amending soil with YWC did not affect root-knot nematode populations in 1996 (Table 4) but significantly increased root-knot and ring nematode populations compared to non-amended soil in 1997 (Table 5). Amending soil with YWC and not flooding or solarizing resulted in highest soil root-knot and ring nematode numbers (Table 5). When soil was solarized and amended with YWC, tomato aboveground biomass was highest regardless of the flooding treatment (Table 6).

A significant increase in soil extractable NO_3-N, P, K, Ca, and Mg measured at the end of 1996 as a result of amending with YWC (data not shown) suggests that the principal benefit of the compost was to improve soil chemical properties in spite

Table 7. Treatment effects on soil root-knot nematode, ring nematode, and stubby root nematode populations after completion of flooding and solarization in 1997. Only four treatments[z] from continuously flooded, non-solarized plots were included, to make a 2 × 2 factorial (Crop × Amendment). Means within columns followed by different letters are significantly different ($P \leq 0.05$) using Duncan's multiple range test and protected Fisher's LSD for interactions.

Source	Level	Root-knot nematode (J2/100 cm^3)	Ring nematodes per 100 cm^3	Stubby-root nematodes per 100 cm^3
Crop	Rice	59 a	52 a	23 A
	Fallow	3 b	16 b	<1 b
Amendment	Compost	24 a	52 a	11 a
	Compost (N)	38 a	16 b	13 a
Crop ×	Fallow × Compost (N)	1 a	3 a	1 a
Amendment	Fallow × Compost	6 a	29 a	<1 a
	Rice × Compost (N)	78 a	29 a	24 a
	Rice × Compost	43 a	75 a	22 a

[z]Treatment descriptions are: Rice = cv. Lemont), Fallow = soil fallowed, Solarize = soil solarization (mesocosms covered with bubble wrap overlain by clear IR-absorbing plastic), Solarize (N) = non-solarized soil, Compost = soil amended with yard-waste compost, Compost (N) = non-composted soil.

of the fact that non-amended plots were well fertilized. YWC apparently may have also improved soil physical conditions (soil structure and water-holding capacity) (Gallaher and McSorley, 1996). McSorley and Gallaher (1995) demonstrated the potential for YWC to improve crop performance in spite of the presence of plant parasitic nematodes. This is demonstrated by the increase ($P \leq 0.05$) in total rice biomass in 1996 (440 versus 305 g/plot) and 1997 (747 versus 502 g/plot) with YWC amendment. Tomato planted in YWC treatments had mean galling index of 2 and had significantly higher above-ground biomass than non-amended treatments (Table 6). It is encouraging that plant (rice and tomato) performance was improved with YWC amendment albeit that soil root-knot and ring nematode populations were not reduced immediately after the flooding regime and that tomato indicator plants presented galling.

SUMMARY

In this experiment the response of soil root-knot, ring, and stubby root nematode populations to flooding, solarization, and amending with YWC were evaluated in confined mesocosms. The results show that flooding and solarizing soil alone or in combination effectively reduce soil nematode densities and galling in indicator plants. However, the effect of flooding on the productivity of a subsequent tomato crop requires further evaluation. Although, planting rice or amending soil with YWC favored the development of some plant parasitic nematodes in this study, the possibility that YWC may help plants tolerate nematodes requires further study. We suggest that for nematode management, flooding could be done for a short time period of 6 to 12 weeks, and no organic amendments are needed to make soils anaerobic. Since we tested

simultaneous flooding and solarization in this experiment, other treatment combinations such as solarization following flooding could be more practical under field conditions. In addition, the efficacy of these treatments for control of other nematode species that commonly occur in sandy soils including awl (*Dolichodorus* spp.) and sting (*Belonolaimus* spp.), that could cause damage to susceptible vegetable crops need to be evaluated.

ACKNOWLEDGMENTS

We appreciate the assistance of F. McGraw, W. Wynn, and J. Brown for setting up the mesocosm facility, installing the datalogger system, and preparing and maintaining the soils and treatments. Additional assistance from V. Chew, S. Edme, and R. Gesh is acknowledged.

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Received: *24.II.1999*

Recibido:

Accepted for publication: *18.V.1999*

Aceptado para publicación: