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Agron. Sustain. Dev. 28 (2008) 221–230
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DOI: 10.1051/agro:2007053

Available online at:
www.agronomy-journal.org

Agronomy for Sustainable Development

Original article

Greenhouse soil solarization: effect on weeds, nematodes and yield of tomato and melon

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(Accepted 26 October 2007)

Abstract – Phase-out of methyl bromide and health concerns related to the use of pesticides are increasing the interest in alternative control strategies. Soil solarization is an effective, safe and cheap technique for the control of soil-borne pathogens and weeds. However, knowledge of the long-term effects of solarization, as well as of repeated solarization cycles, is scarce. Such knowledge should in particular help to minimize the number of solarization treatments. Therefore, we tested the residual effect of a single solarization treatment and the effects of two or three solarization cycles on root-knot nematodes, weeds and crop yield for three years on greenhouse-grown tomato and melon. Soil solarization was applied for either one, two or three consecutive years on a soil infested by the root-knot nematode *Meloidogyne javanica* and many annual and perennial weed species. An untreated soil was used as a control. At the end of each crop cycle yield parameters were recorded, weeds were identified and counted, and nematode infestation was evaluated. Our results show that a single solarization treatment significantly increased yields by +116%, and strongly reduced nematode infestation of −99% of infested plants and of −98% of the root gall index in the following melon crop. It also suppressed annual weed emergence three years later. Plant yields from two- and three-year solarized soil were always higher than nonsolarized control: +284% and +263%, respectively, for tomato, and +162% and +368%, respectively, for melon. Further, two- and three-year solarization treatments almost completely suppressed the infestation of the *M. javanica* nematode in tomato, and reduced the nematode effect in melon by −86% and −79%, respectively. Repeated solarization treatments also resulted in a high reduction of emergence of most weed species in all crop cycles. A single soil solarization treatment was shown to be effective for a long-term sustainable management of weeds, whereas the time-limited effectiveness against root-knot nematodes can be enhanced through two- or three-year repeated treatments.

solarization / nematodes / weeds / yield / tomato / melon

1. INTRODUCTION

Root-knot nematodes (*Meloidogyne* spp.) and weeds can cause heavy yield losses to many crops. Control of these pests is generally based on chemical treatments, but environmental and health hazards due to the extensive use of pesticides are forcing growers to rely on nonchemical pest management approaches (Katan, 1999). Soil solarization is a cost-saving and environmentally safe nonchemical soil disinfestation method that, under appropriate conditions, can ensure an effective control of a wide range of pathogens, weeds and arthropod pests (Camprubi et al., 2007; Stapleton, 2000). Other soil-heating treatments have been demonstrated to be as effective as solarization for the control of soil-borne diseases and weeds (Luvisi et al., 2006; Kolberg and Wiles, 2002), but are more expensive and difficult to use for growers. Soil temperature increase caused by solarization must be sufficiently high and prolonged to cause irreversible damage to most soil-borne pathogens (Nico et al., 2003). Therefore, this technique is particularly suitable for the Mediterranean climate, where the occurrence of high summer temperatures can ensure an effective control of fungi, nematodes and weeds (Shlevin et al., 2003; Oka et al., 2007; Roe et al., 2004).

Evaluation of the persistence of soil solarization effects is particularly useful in intensive greenhouse cropping systems in Southern Italy, where short intervals between crops necessitate the need to reduce as much as possible the number of solarization treatments by extending their residual effects. Long-term effects of soil solarization were previously investigated mostly on soil-borne fungal pathogens in the field (Freeman et al., 1990; Tjamos and Paplomatas, 1988), whereas little information is available on the residual effect of solarization

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Figure 1. Solarization treatment in the metal-plastic greenhouse.

treatment on weeds and phytoparasitic nematodes in the greenhouse.

Solarization repeated for two or more consecutive years could improve the effectiveness of thermal treatment on heat-resistant weed species or on root-knot nematodes (*Meloidogyne* spp.), that easily survive and reinfest the soil after a single solarization treatment (Rubin and Benjamin, 1983; Stapleton and DeVay, 1995).

A three-year experiment was undertaken to investigate (a) the long-term effect of a single solarization treatment and (b) the effect of solarization repeated for two or three consecutive years on root-knot nematodes, weeds and yield parameters in a greenhouse tomato – melon succession in Southern Italy.

2. MATERIALS AND METHODS

The experiment was undertaken in a metal-plastic (200-μm-thick low-density polyethylene transparent film) greenhouse located in Metaponto (40°20'N; 16°48'E) in Southern Italy (Fig. 1). The alkaline (pH 8.4) sandy soil was heavily infested (3.1 eggs and juveniles cm^{-3} soil) by the root-knot nematode *Meloidogyne javanica* (Treub) Chitw.

On 23 July 1998 the soil was ploughed at 40 cm depth, uniformly rotavated and irrigated to field capacity at the same depth through a drip irrigation system with dripper lines 0.5 m apart and emitters (3 L h^{-1} water flow rate) spaced 0.20 m from each other. The soil surface was then divided into 16 plots (6×4 m), spaced 1 m apart and grouped into four blocks. The surface of 12 plots, 3 in each block, was then covered with a low-density polyethylene (LDPE) 50-μm-thick transparent film and solarized for 79 days (from 24 July to 11 October 1998) in closed greenhouse conditions. In summer 1999 the solarization treatment was repeated on 8 of the plots solarized in the previous year, 2 in each block, covering the soil surface with an ethylene-vinyl acetate (EVA) 30-μm-thick transparent plastic film for 37 days, starting from 17 July. In 2000 only 4 plots, one in each block, were solarized with EVA film (as before) for 34 days, also starting from 17 July. In 1999 and 2000 LDPE, currently used for solarization in the Metaponto area, was replaced by a more thermally efficient EVA film (Russo et al., 2005) with the aim of shortening the solarization length and allowing cultivation of an autumn tomato crop. Therefore, four experimental treatments, arranged in a complete randomized block design, were finally provided: nonsolarized soil, soil solarized only in 1998, soil solarized consecutively in 1998 and 1999 and soil solarized for three consecutive years (1998, 1999 and 2000).

After solarization in 1998, melon (*Cucumis melo* L. var. reticulatus Naud.) cv Baggio F1 was cultivated from 3 March 1999 to 8 July 1999. In 1999 and 2000 tomato (autumn–winter) and melon (spring–summer) were cultivated after solarization. Tomato (*Lycopersicon esculentum* Mill.) cv Naxos was transplanted on 28 August 1999 and 24 August 2000 and uprooted on 4 January 2000 and 26 January 2001, respectively. In 2000, melon cv Baggio F1 was transplanted on 14 March and cultivated until 26 June, whereas in 2001, cv Drake F1 was directly sown on 23 March and uprooted on 15 July. Tomato was transplanted in rows 1 m apart (3.3 plants m^{-2}), and melon was transplanted or sown in rows 2 m apart (0.5 plants m^{-2}). Soil was left undisturbed after each solarization, mulched with a 50-μm-thick black LPDE film during each crop cycle and slightly rotavated only at its end. All selected tomato and melon cultivars were reported as being susceptible to *M. javanica*.

Soil temperatures were monitored at 30-min intervals during each solarization period. In 1998, temperatures at 5, 20 and 35 cm depth were recorded by a geothermograph (Salmoiraghi Instruments, Milan, Italy), whereas in 1999 and 2000, PT-100 probes and a CR- 10X data-logger (Campbell Scientific, Inc., USA) were used to record soil temperatures at 10, 20 and 30 cm depth.

At the end of each crop cycle, number and weight of marketable fruits, average fruit weight and soluble solids content (°Brix) were assessed on samples taken from 3- or 12-m^2 sampling areas, for tomato and melon, respectively. Plants infected by *M. javanica* were counted and percent infestation was calculated for each plot. Nematode infestation on crop roots (root gall index) was estimated on 10 tomato and 6 melon plants $plot^{-1}$, according to a 0–5 scale in which 0 = no galls, 1 = 1 to 2 galls, 2 = 3 to 10 galls, 3 = 11 to 30 galls, 4 = 31 to 100 galls and 5 = > 100 galls (Taylor and Sasser, 1987). After each solarization treatment and at the end of each crop cycle weeds were counted and classified from a 2-m^2 sampling area in the center of each plot and from the nonmulched soil between the rows. Weed biomass was completely removed from the soil after each observation.

Since the solarization treatment performed in 1998 differed from those performed in 1999 and 2000 in film type and thickness and in duration, the effect of the 1998 treatment was distinguished from those of the 1999 and 2000 treatments, comparing data from plots treated only in 1998 with those from untreated soil separately. Weed and nematode data were statistically analyzed after L_n (x + 1) transformation for homogenization of error variances. The Student's *t* test or ANOVA were followed by mean comparison tests (Fisher's Least Significant Difference Test at $P \leqslant 0.05$).

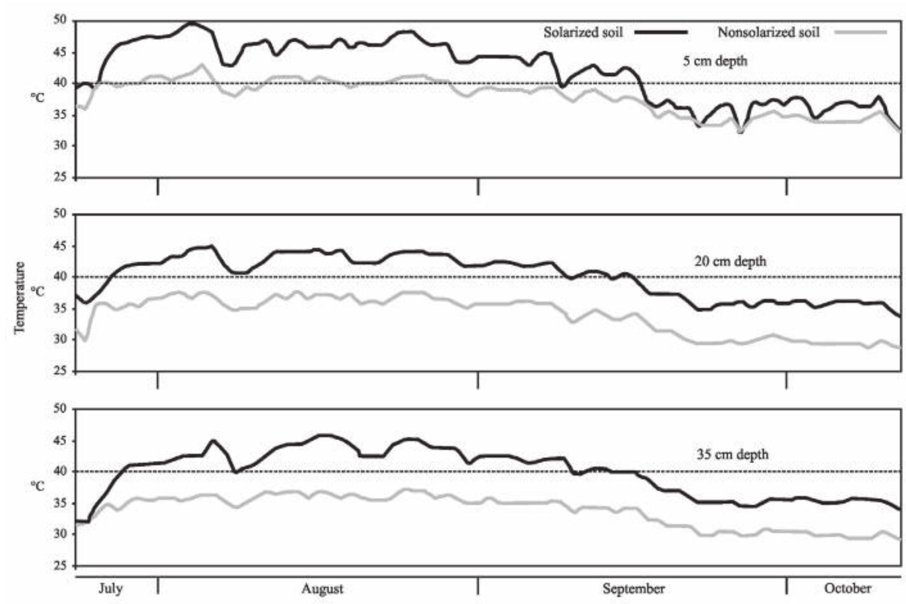

Figure 2. Daily mean soil temperatures at 5, 20 and 35 cm depth during solarization in 1998.

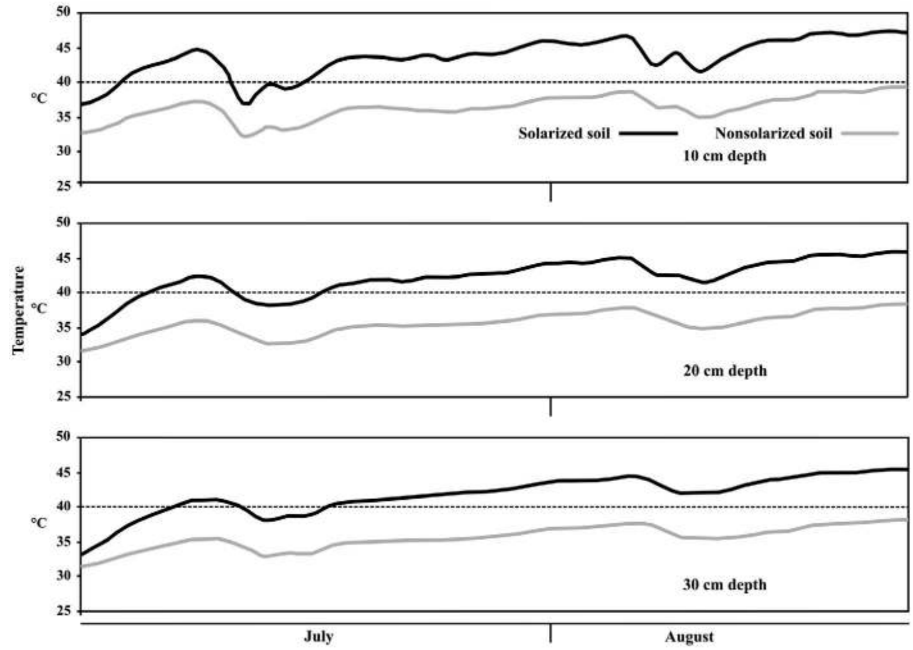

Figure 3. Daily mean soil temperatures at 10, 20 and 30 cm depth during solarization in 1999.

3. RESULTS AND DISCUSSION

3.1. Effect on soil temperatures

During solarization in 1998 average daily soil temperatures were 41.9 and 37.8 °C at 5 cm depth and 39.9 and 33.6 °C at 20 cm depth, respectively, in solarized and nonsolarized soil (Fig. 2). Mean daily values at 35 cm depth were similar to 20 cm depth, but daily excursions were less pronounced (data not shown). Soil temperature differences between solarized and nonsolarized soil were larger during the first 40 days of solarization and decreased after the first decade of September. Maximum temperatures, occurring in the first (5 and 20 cm) or the third (30 cm) week of August, were 59 and 46 °C (5 cm), 49 and 40 °C (20 cm) and 49 and 39 °C (35 cm), respectively, in solarized and nonsolarized soil. In 1999, daily soil average temperature was 43.6, 41.6 and 40.3 °C in solarized soil and 36.4, 35.2 and 34.3 °C in nonsolarized soil, respectively, at 10, 20 and 30 cm depth (Fig. 3). The difference between treated and untreated soil was on average 7.1, 6.4 and

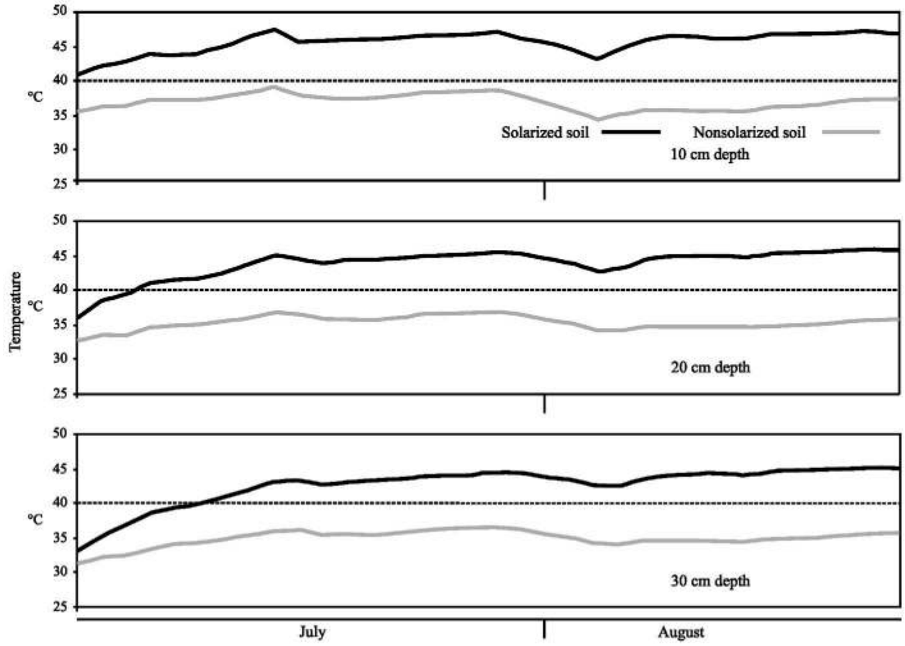

Figure 4. Daily mean soil temperatures at 10, 20 and 30 cm depth during solarization in 2000.

6.0 °C, respectively, at 10, 20 and 30 cm depth, being more evident only from the beginning of August onwards. Maximum temperatures were 47.3, 45.2 and 43.9 °C in solarized soil, and 39.4, 37.9 and 36.9 °C in nonsolarized soil, respectively, at 10, 20 and 30 cm depth. In 2000 average daily temperature values were 46.0, 44.1 and 42.5 °C in solarized soil and 37.0, 35.5 and 34.8 °C in nonsolarized soil, with an average difference of 9.0, 8.6 and 7.7 °C at 10, 20 and 30 cm depth, respectively (Fig. 4). As in 1999, differences were larger at the end of the solarization period. Temperature peaks were 47.9, 46.2 and 45.1 °C in solarized soil, and 39.1, 37.1 and 36.5 °C in nonsolarized soil, respectively, at 10, 20 and 30 cm depth.

Soil temperatures at 0–30 cm depth exceeded values estimated as effective for suppression of most soil pathogens only in the first 40 days of solarization. LD_{95} values of 813, 281 and 32.4 min at 39, 42, and 46 °C, respectively, were found for the root-knot nematode *M. incognita* Kofoid et White Chitw. after the application of constant temperature-time dosages to infested soil (Ruiz et al., 2003), whereas a 30-min exposure at 60 °C was reported to be lethal for the potato cyst-nematode *Globodera rostochiensis* Wollenweber (Evans, 1991). LD_{50} was found at 50 to 66 °C at 12 hours of exposure for eight common weed seeds (Egley, 1990), and a 30-min exposure at a 30 to 90 °C range of temperatures decreased *Cyperus rotundus* L. tuber viability in an inverse linear manner (Rubin and Benjamin, 1984). Number of hours of lethal temperatures depends on seasonal weather conditions, but effectiveness of the treatment can also be related to other factors, including soil structure, color, organic matter content and seedbed preparation (Grinstein and Hetzroni, 1991).

3.2. Effect on yield response

Melon following solarization in 1998 showed significantly higher yield (+116%) and fruit soluble solids content (+25%) and a lower mean fruit weight (−6%) in solarized than in nonsolarized plots (Tab. I). Compared with the control, a single solarization treatment in 1998 resulted in significantly higher yield (+131%) and mean fruit weight (+62%) and lower soluble solids content (−23%) in the 1999 tomato crop, but yield parameters were not significantly different in the 2000 tomato crop or in melon in either 2000 or 2001. Tomato and melon yields were significantly higher in plots solarized for two (+284% and +162%, respectively, in tomato and melon) or three consecutive years (+263 and +368%) than in nonsolarized plots, due to a higher number of heavier fruits per plant (Tab. II). Yield parameters of two- and three year-solarized plots did not significantly differ, either in tomato or melon. Soluble solids content of fruits from two- and three year-solarized soil was always significantly higher than in nonsolarized plots in melon and lower in tomato, whereas no significant differences were found between the two- and three-year-treatments.

Larger fruit size and consequent higher water content can explain the lower soluble solids content of tomato fruits from solarized soil, whereas the higher soluble solids content of melon fruits was due to the presence of larger plants bearing a higher number of smaller size fruits consequent to the growth stimulation effect of solarization. Irregular ripening following early nematode attack and plant collapse may explain the low quality of melon fruits from nonsolarized plots. The beneficial effect of thermal treatment on crop yield can be related not only to the suppression of nematodes and weeds, but also

Table I. Residual effect of soil solarization performed in 1998 on yield parameters of the following tomato and melon crops.

Solarization treatments	Marketable yield								Fruit quality							
	Weight ($t\ ha^{-1}$)				Fruits per plant (n.)				Mean weight (g)				Soluble solids (°Brix)			
	Tomato		Melon		Tomato		Melon		Tomato		Melon		Tomato		Melon	
March 1999–July 1999																
Nonsolarized	-	-	17.7	b	-	-	2.5	b	-	-	1480	a	-	-	9.3	b
Solarized	-	-	38.2	a	-	-	5.1	a	-	-	1390	b	-	-	11.6	a
August 1999–June 2000																
Nonsolarized	8.1	b	11.2	ns	4.2	b	1.7	ns	65	b	1320	ns	4.7	a	8.6	ns
Solarized	18.7	a	13.2	ns	6.5	a	2.1	ns	105	a	1130	ns	3.6	b	9.0	ns
August 2000–July 2001																
Nonsolarized	16.6	ns	10.8	ns	6.1	ns	1.5	ns	81	ns	1920	ns	5.5	a	9.8	ns
Solarized	10.3	ns	14.4	ns	4.0	ns	1.5	ns	76	ns	1960	ns	4.9	b	10.0	ns

Means followed by different letters in the same column within each crop cycle are statistically different at $P \leq 0.05$ (Student's *t* Test).

Table II. Effect of soil solarization repeated for two or three consecutive years on yield parameters of tomato and melon crops.

Solarization treatments	Marketable yield								Fruit quality							
	Weight ($t\ ha^{-1}$)				Fruits per plant (n.)				Mean weight (g)				Soluble solids (°Brix)			
	Tomato		Melon		Tomato		Melon		Tomato		Melon		Tomato		Melon	
August 1999–June 2000																
Nonsolarized	8.1	b	11.2	b	4.2	b	1.7	b	65	b	1320	ns	4.7	a	8.6	b
Solarized in 1998 and 1999	31.1	a	29.3	a	9.4	a	5.0	a	108	a	1190	ns	3.5	b	10.8	a
August 2000–July 2001																
Nonsolarized	16.6	b	10.8	b	6.1	b	1.5	b	81	b	1920	ns	5.5	a	9.8	b
Solarized in 1998 and 1999	51.7	a	46.8	a	12.0	a	4.5	a	129	a	2020	ns	4.0	b	12.8	a
Solarized in 1998, 1999 and 2000	60.3	a	50.6	a	14.6	a	5.2	a	124	a	1900	ns	4.2	b	12.5	a

Means followed by different letters in the same column within each crop cycle are statistically different at $P \leqslant 0.05$ (Student's *t* Test in 1999–2000; Fisher's LSD Test in 2000–2001).

to the release of nutrients induced by high soil temperatures (Stapleton and DeVay, 1984), and/or to the suppression of other soil pathogens not evaluated in this experiment.

The residual effect of solarization on crop yield was extended to the two crop cycles immediately following the treatment. An increase in cotton crop yield was observed for as long as 3 years after a soil solarization treatment in Israel (Katan et al., 1983), and a high residual effect of an 8-week solarization was also found in a greenhouse experiment carried out in Cyprus (Ioannou, 2000).

3.3. Effect on nematode population

Tomato and melon roots from nonsolarized soil were severely infested by *M. javanica* in all crop cycles (Tabs. III, IV). Plots solarized in 1998 showed a strong reduction of the percentage of infected plants (−99%) and severity of root galling (−98%) in the following melon crop (Tab. III). Compared with the control, the single solarization treatment in 1998 resulted in a significantly lower number of root galls only in the 1999 tomato crop (−22%), whereas number of galls and percent infected plants were not significantly different in the 2000 tomato crop or in melon in either 2000 or 2001. Percentages of infected plants and the root gall index were always significantly ($P \leq 0.05$) lower in soil solarized for two or three consecutive years than in untreated plots, both in tomato and melon crops (Tab. IV). Nematode infestation parameters were significantly lower (−61% and −70%, respectively, for infected plant percentage and root gall index) in three-year solarized plots than in two-year treated soil only in melon in 2001, whereas no significant difference was found in tomato in 2000.

Previous evidence was confirmed by the limited soil solarization effect on root-knot nematodes that emerged from this study. In the above cited greenhouse experiment in Cyprus soil, 8-week solarization reduced root-knot nematode infestation on tomato by only 50% (Ioannou, 2000). The effectiveness of the heat treatment may change for different target nematodes, as lethal temperatures and exposure times were found to be related to nematode species (D'Addabbo et al., 2005; Greco et al., 1998). Combination with pre- or post-plant nematicide applications or integration with other nonchemical techniques may enhance the nematicidal effect of solarization. Combination of 7-day soil solarization with reduced dosages of 1,3-dichloropropene significantly reduced root-knot nematode populations in tomato and pepper (*Capsicum annuum* L.) crops when compared with an untreated control (Chellemi and Mirusso, 2006). A 30-day soil solarization combined with

Table III. Residual effect of soil solarization performed in 1998 on the infestation of *Meloidogyne javanica* in tomato and melon crops.

Solarization treatments	Infested plants (%)				Root gall index			
	Tomato		Melon		Tomato		Melon	
	March 1999–July 1999							
Nonsolarized	-	-	98.4	a	-	-	4.9	a
Solarized	-	-	0.6	b	-	-	0.1	b
	August 1999–June 2000							
Nonsolarized	100.0	ns	100.0	ns	5.0	a	5.0	ns
Solarized	92.5	ns	100.0	ns	3.9	b	4.7	ns
	August 2000–July 2001							
Nonsolarized	100.0	ns	100.0	ns	5.0	ns	5.0	ns
Solarized	100.0	ns	100.0	ns	5.0	ns	5.0	ns

Means followed by different letters in the same column within each crop cycle are statistically different at $P \leq 0.05$ (Student's *t* Test).

Table IV. Effect of soil solarization repeated for two or three consecutive years on the infestation of *Meloidogyne javanica* in tomato and melon crops.

Solarization treatments	Infested plants (%)				Root gall index			
	Tomato		Melon		Tomato		Melon	
	August 1999–June 2000							
Nonsolarized	100.0	a	100.0	a	5.0	a	5.0	a
Solarized in 1998 and 1999	0.0	b	14.3	b	0.0	b	0.7	b
	August 2000–July 2001							
Nonsolarized	100.0	a	100.0	a	5.0	a	5.0	a
Solarized in 1998 and 1999	3.3	b	54.4	b	0.3	b	2.3	b
Solarized in 1998,1999 and 2000	0.0	b	21.4	c	0.0	b	0.7	c

Means followed by different letters in the same column within each crop cycle are statistically different at $P \leq 0.05$ (Student's *t* Test in 1999–2000; Fisher's LSD Test in 2000–2001).

organic amendments was more effective than solarization or amendments alone at reducing *M. incognita* and *M. javanica* populations in soil and galling indices on tomato and pepper plants (Oka et al., 2007).

Rapid soil recolonization by nematodes after the thermal treatment is the main reason for the short residual effect of solarization on root-knot nematodes, as *M. javanica* infestation on tomato cultivated only one year later was slightly affected by solarization performed in the previous year. The beneficial effect of solarization on nematodes can be enhanced by repeating thermal treatment for two or three consecutive years, as continuous solarization treatments do not allow the recolonization of soil by nematodes and progressively reduce population densities to under the economic threshold. In our experiment, two consecutive solarization treatments resulted in almost gall-free tomato plants and the nematicidal effect was further increased by a third solarization cycle.

3.4. Effect on weeds

At the end of solarization in 1998 only *C. rotundus* L. survived under the plastic film, whereas uncovered plots were infested by many annual and perennial weeds, with a prevalence of *C. rotundus* and *Cynodon dactylon* (L.) Pers. (Tab. V). In the solarized soil, emergence of annual weeds was completely suppressed at the end of the subsequent melon crop, and only *C. rotundus*, *C. dactylon* (at a density significantly lower than in the nonsolarized soil) and *Phragmites australis* (Cav.) Trin. were found. In soil solarized only in 1998, several species were found before tomato transplanting in 1999, but the density of *C. dactylon*, *Digitaria sanguinalis* (L.) Scop., *Echinochloa crus-galli* L. Beauv. and *Portulaca oleracea* L. was significantly lower than in nonsolarized soil (Tab. VI). The density of *C. dactylon* and *D. sanguinalis* was also significantly reduced following tomato in 1999 and after solarization in 2000. Emergence of annual weeds was also significantly lower or completely suppressed in melon in 2000, whereas only the density of *C. dactylon* was significantly lower after tomato in 2000 and melon in 2001. Soil treated for two consecutive years was completely free of weeds after the second treatment in 1999, and few weed species were present also in the following tomato, with *C. dactylon* and *D. sanguinalis* showing a significantly lower density than in the control (Tab. VII). Melon transplanted in March 2000 was infested mostly by annual weeds, whose emergence, including *C. rotundus*, was significantly reduced or completely suppressed in the two-year solarized soil.

At the end of solarization in 2000 a significant suppression of weed emergence was found in soil solarized either for two or three consecutive years. The density of *C. dactylon* was significantly lower in solarized plots after the following tomato and melon crops, whereas the density of *D. sanguinalis*, *P. oleracea* and *S. nigrum* was significantly reduced only after

Table V. Weed emergence in uncultivated soil and in melon crops after solarization in 1998 (plants m^{-2}).

Weed species	No crop								Melon crop			
	October 1998				February 1999							
	nonsolarized		solarized		nonsolarized		solarized		nonsolarized		solarized	
Perennial species												
Phragmites australis (Cav.) Trin.	0.3	a	0.0	b	-	-	-	-	1.7	ns	2.0	ns
Cirsium arvense (L.) Scop.	-	-	-	-	0.5	a	0.0	b	3.0	a	0.0	b
Cynodon dactylon (L.) Pers.	1.5	a	0.0	b	-	-	-	-	2.7	a	1.7	b
Cyperus rotundus L.	2.3	a	1.5	b	-	-	-	-	8.0	a	5.3	b
Convolvulus sp.	0.3	a	0.0	b	-	-	-	-	-	-	-	-
Annual species												
Setaria viridis (L.) Beauv.	-	-	-	-	-	-	-	-	7.7	a	0.0	b
Solanum nigrum L.	-	-	-	-	-	-	-	-	15.7	a	0.0	b
Sonchus oleraceus L.	-	-	-	-	-	-	-	-	1.7	a	0.0	b
Echinochloa crus-galli (L.) Beauv.	0.5	a	0.0	b	1.8	a	0.0	a	5.0	a	0.0	b
Portulaca oleracea L.	0.5	a	0.0	b	-	-	-	-	-	-	-	-
Heliotropium europaeum L.	0.3	a	0.0	b	-	-	-	-	-	-	-	-
Euphorbia sp.	0.5	a	0.0	b	-	-	-	-	-	-	-	-
Vicia sativa L.	-	-	-	-	150	a	20.0	b	6.0	a	0.0	b
Melilotus sulcatus L.	-	-	-	-	-	-	-	-	2.3	a	0.0	b
Chenopodium album L.	-	-	-	-	-	-	-	-	3.3	a	0.0	b
Amaranthus retroflexus L.	-	-	-	-	-	-	-	-	2.7	a	0.0	b

Means followed by different letters in the same row within each observation date are statistically different at $P \leq 0.05$ (Student's *t* Test).

Table VI. Residual effect of soil solarization performed in 1998 on weed emergence in the following tomato and melon crops (plants m^{-2}).

Weed species	No crop(1)				Tomato				Melon			
	nonsolarized		solarized		nonsolarized		solarized		nonsolarized		solarized	
					August 1999–June 2000							
Perennial species												
Cynodon dactylon (L.) Pers.	21.0	a	1.5	b	2.6	a	1.3	b	3.0	a	1.7	b
Cyperus rotundus L.	5.0	ns	4.0	ns	1.2	ns	0.9	ns	4.2	ns	1.6	ns
Annual species												
Digitaria sanguinalis (L.) Scop.	34	a	10.5	b	3.3	a	0.3	b	6.6	a	2.0	b
Echinochloa crus-galli (L.) Beauv.	49	a	0.0	b	-	-	-	-	6.2	a	0.4	b
Portulaca oleracea L.	76.0	a	21.0	b	-	-	-	-	1.2	a	0.6	b
Others(2)	-	-	-	-	-	-	-	-	1.4	ns	0.7	ns
					August 2000–July 2001							
Perennial species												
Cynodon dactylon (L.) Pers.	1.0	a	0.0	b	-	-	-	-	2.4	ns	1.2	ns
Cyperus rotundus L.	8.0	ns	11.3	ns	1.0	ns	1.3	ns	8.8	ns	7.5	ns
Annual species												
Digitaria sanguinalis (L.) Scop.	26.0	a	4.7	b	1.2	ns	0.6	ns	173.6	a	60.2	b
Portulaca oleracea L.	22.3	ns	14.7	ns	-	-	-	-	13.6	ns	9.8	ns
Solanum nigrum L.	-	-	-	-	-	-	-	-	13.6	a	2.0	b

Means followed by different letters in the same row within each observation date are statistically different at $P \leq 0.05$ (Student's *t* Test); (1) before tomato transplanting; (2) including *Setaria viridis* (L.) Beauv., *Amaranthus retroflexus* L., *Solanum nigrum* L. and *Chenopodium album* L.

melon (Fig. 5). No suppressive effect of the two- and three-year solarization treatments was found on *C. rotundus*.

In previous trials, 98-day soil solarization reduced weeds present in collard green (*Brassica oleracea acephala* L.) by 91% and increased crop yield in the following year, being more effective than a herbicide treatment (Stevens et al., 1990). In another experiment in Syria, 50-day solarization reduced total weed density by 80% and total weed biomass by 94 and 85% in lentil and faba bean, respectively (Linke, 1994). Tolerance of *C. rotundus* and high susceptibility of *C. dactylon* to solarization were also reported (Rubin and Benjamin, 1984). Weed suppression was probably also affected by the stimulating effect of solarization on crop growth, that likely resulted in a higher competitive ability of tomato and melon crop stands in solarized soil. Moreover, seasonal climate and cultural practices may also influence weed species composition and density.

The long-term effect of single soil solarization was much more pronounced on weeds than on nematodes, since a reduction or a total suppression of annual species and some

Table VII. Effect of soil solarization repeated for two or three consecutive years on weed emergence in the following tomato and melon crops (plants m^{-2}).

Weed species	No crop(1) nonsolarized		No crop(1) solarized in 1998 and 1999		No crop(1) solarized in 1998, 1999 and 2000	Tomato crop nonsolarized		Tomato crop solarized in 1998 and 1999		Tomato crop solarized in 1998, 1999 and 2000		Melon crop nonsolarized		Melon crop solarized in 1998 and 1999		Melon crop solarized in 1998, 1999 and 2000	
August 1999 - June 2000																	
Perennial species																	
Cynodon dactylon (L.) Pers.	21.0	a	0.0	b	-	2.6	a	0.0	b	-	-	3.0	a	0.0	b	-	-
Cyperus rotundus L.	5.0	a	0.0	b	-	1.2	ns	0.8	ns	-	-	4.2	a	0.0	b	-	-
Annual species																	
Digitaria sanguinalis (L.) Scop.	34.1	a	0.0	b	-	3.3	a	0.0	b	-	-	6.6	a	1.6	b	-	-
Echinochloa crus-galli (L.) Beauv.	49.0	a	0.0	b	-	-	-	-	-	-	-	6.2	a	0.3	b	-	-
Portulaca oleracea L.	76.0	a	0.0	b	-	-	-	-	-	-	-	1.2	a	0.7	b	-	-
Others(2)	-	-	-	-	-	-	*	-	-	-	-	1.4	a	0.0	b	-	-
August 2000–July 2001																	
Perennial species																	
Cynodon dactylon	1.0	a	0.0	b	0.0	b	-	-	-	-	-	-	2.4	a	0.7	ab	0
Cyperus rotundus	8.0	a	11.3	a	0.0	b	1.0	ns	1.2	ns	0.9	ns	8.8	ns	10.0	ns	9.7
Annual species																	
Digitaria sanguinalis	26.0	a	0.3	b	0.0	b	1.2	a	0.1	b	0.0	b	173.6	a	25.1	b	2.4
Portulaca oleracea	22.3	a	2.3	b	0.0	b	-	-	-	-	-	-	13.6	a	1.9	b	0.0
Solanum nigrum	-	-	-	-	-	-	-	-	-	-	-	13.6	a	3.1	b	2.4	b

Means followed by different letters in the same row within each observation date are statistically different at $P \leq 0.05$ (Fisher's LSD Test). (1) Before tomato transplanting. (2) Including *Setaria viridis* (L.) Beauv., *Amaranthus retroflexus* L., *Solanum nigrum* L. and *Chenopodium album* L..

Figure 5. Weed emergence in 2001 melon crop.

perennial species were still found on melon cultivated after two years, and also later for *C. dactylon*. In a previous experiment 5-week solarization maintained soil free of weeds for at least three years in an olive orchard (Lopez-Escudero and Blanco-Lopez, 2001). The effects of repeated solarization were less evident on weeds due to the prolonged residual effect of single treatment.

Soil solarization was confirmed as a valid tactic for management of root-knot nematodes and weeds in the greenhouse. Limits to a further diffusion of this technique are still represented by treatment duration and final disposal of the plastic film. Integration with reduced amounts of chemicals may shorten the solarization period without reducing its efficacy (Benlioglu et al., 2005; Chellemi et al., 1997; Minuto et al., 2000), whereas use of innovative biodegradable or photodegradable films (Castronuovo et al., 2005) may combine thermal performance on nematodes and weeds and yield increase with a simple and environmentally safer plastic disposal.

4. CONCLUSION

Under the warm weather conditions of Southern Italy, solarization is an effective technique for an environmentally sustainable and cost-saving disinfestation of soil in greenhouse cropping systems, providing a satisfactory control of most weeds and a sufficient short-term nematode suppression. Progressive phasing out of most of the presently available chemicals and heavier root-knot nematode infestations that are likely to occur in warmer summer seasons will further enhance the importance of this technique in the near future. Two- or three-yearly treatments can be enough for an effective control of weeds, whereas annual treatments are required for nematodes. Use of high thermal-efficiency films or combination with low doses of chemicals or other nonchemical methods can prolong the residual effects of single solarization on nematodes. Solarization repeated for two consecutive years can considerably enhance the effect on nematodes and crop yield. Application of an additional treatment in the third year results in no further improvement.

Acknowledgements: This work was carried out within the research project "Innovative and eco-compatible technologies for extra-seasonal and quality vegetable production" (TEPORE), POM Measure 2. The authors shared the work equally.

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