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Long Time Effect of Soil Solarization Integrated with Dazomet or Chicken Manure on Yield, Weeds and Root-Knot Nematodes in Tomato and Melon

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Abstract

Effects of 5-week soil solarization, either alone or combined with dazomet or a chicken manure compost, on tomato and melon yield, root-knot nematode infestation and weeds were investigated along three crop cycles in a plastic greenhouse infested by *Meloidogyne javanica* in Southern Italy. Solarization treatment, either alone and combined with dazomet or organic amendment, always resulted in a significant increase of marketable crop yield, and its effect lasted up to two years from the treatment. Nematode population indices and number of root galls were always lower in solarized soil than in untreated control. Organic amendment alone suppressed soil nematode population only in the first two crop cycles, though less than solarization and with no significant reduction of gall formation. Dazomet alone resulted in a yield increase only in the first tomato crop, with no significant reduction of soil nematode density and root galls. Solarization treatment completely suppressed the emergence of all the annual and perennial weed species, though *C. rotundus* was controlled only immediately after the treatment. Suppressivity of SOL on annual weeds and the perennial *C. dactylon* was extended to the tomato and melon crop following the treatment, but persisted on *D. sanguinalis* and *P. oleracea*, also in the third crop. Combination of solarization with dazomet or chicken manure compost did not enhance the suppressive effect on weeds. Solarization confirmed to provide an effective suppression of root-knot nematodes and weeds in the greenhouse vegetable crop systems of warm climate regions, with no need to be combined with other control tools.

Key-words: greenhouse, solarization, dazomet, chicken manure, yield, weeds *Meloidogyne javanica*, melon, tomato.

1. Introduction

Soil solarization (SOL) is a cost-saving and environmentally safe technique for a nonchemical soil disinfestations (Katan and DeVay, 1991). Under appropriate climate conditions SOL can ensure an effective control of a wide range of pathogens, weeds and nematodes in different agricultural systems (Stapleton, 2000).

Root-knot nematodes (*Meloidogyne* spp.) are spread worldwide and cause a large part of the annual yield losses attributed to nematode damage (Trudgill and Blok, 2001). Environmental and health concerns imposed the withdrawal of most nematicides and soil fumigants available for the control of these phytoparasites and emphasized the need for alternative safer control strategies, including the use of SOL (Noling and Becker, 1994). Several field reports stated that root-knot nematode infestation may be consistently reduced for two consecutive years after the heat treatment (Stevens et al., 2003). However, the rapid recolonization of the soil following SOL may reduce its residual effectiveness, mainly in greenhouse conditions (Candido et al., 2008; Ioannou, 2000).

The effects of SOL against root-knot nematodes may be furtherly enhanced by the combi-

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nation with other control tools, as low doses of fumigant nematicides, among which also dazomet (DAZ), or organic amendments.

Dazomet (DAZ) is a granular methyl isothiocyanate precursor known since the 60s as a broad spectrum fumigant with limited environmental effects (Ruzo, 2006), active on soilborne pathogens, weeds and also root-knot nematodes (Giannakou et al., 2002; Gilreath et al., 2004).

Many composts from agroindustrial residues like chicken manure (CM) were found to be potentially suppressive on root-knot nematodes (Nico et al., 2004; Oka and Yermiyahu, 2002).

The combination of SOL with reduced doses of DAZ proved to enhance the suppressivity of thermal treatment either on root-knot nematodes (Yucel et al., 2007) and weeds (Benlioğlu et al., 2005). Integration of SOL with raw or composted CM was also proved to enhance the effect of thermal treatment on root-knot nematodes in various experiments, either in field (Gamliel and Stapleton, 1993) and in greenhouse (Oka et al., 2007; Kafikavalci, 2007).

However, most of investigations on the combined use of SOL and DAZ or CM were limited to a single crop cycle, with no or few information about the residual nematicidal and agronomical effects of these combined treatments on the following crop cycles. Therefore, a three-year greenhouse experiment was undertaken in order to investigate the effect of combination of SOL with reduced rates of DAZ or CM soil amendments on yield parameters and infestation of the root-knot nematode *M. javanica* (Treub) Chitw. along three different crop cycles.

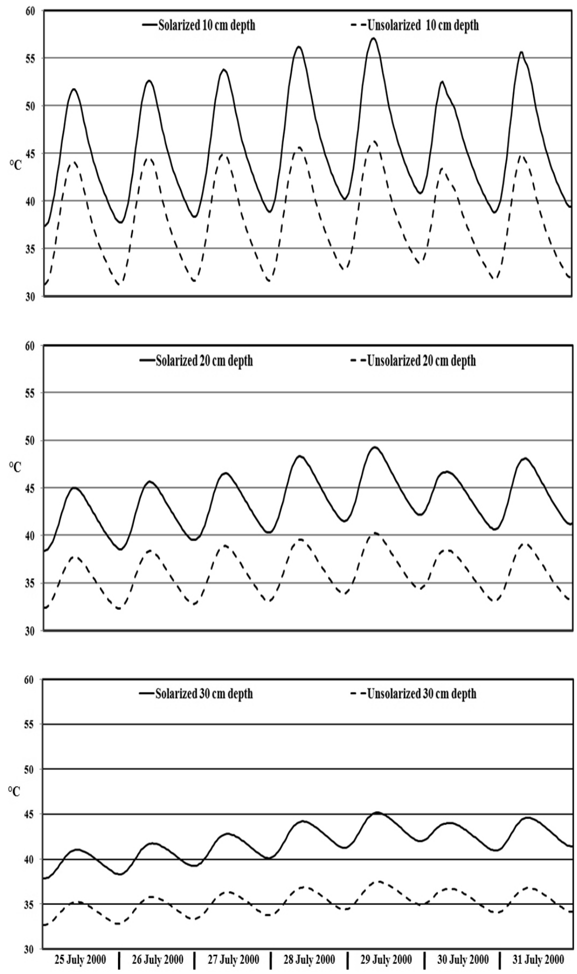

Figure 1. Temperature trend during the representative week (25 July - 31 July 2000) at 10 cm depth.

2. Materials and methods

The experiment was undertaken in a metal-plastic (200-μm thick low-density polyethylene transparent film) greenhouse located at Metaponto (40°24' N, 16°28' E) in Southern Italy. The alkaline (pH 8.4) sandy soil was poor at organic matter (3.3 g kg^{-1}) and nitrogen (0.5 g/kg) and heavily infested (3.6 eggs and juveniles cm^{-3} soil) by *M. javanica*.

Soil was ploughed at 30 cm depth and uniformly rotavated after removing plant residues of the previous melon crop. Soil surface was then divided into three blocks, each subdivided into six 6 × 4 m plots, spaced 1 m apart. Two plots of each blocks were treated with 50 g m^{-2} granular DAZ, two others were amended with 40 t ha^{-1} of a CM-based compost (CM, grape and olive pomace and grapestone meal) and the last two were left untreated. DAZ and CM compost were incorporated into the soil by rotavation and then plots were irrigated to field capacity at 30 cm 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. A 34-day SOL was then applied to a half of each block by covering with a 35 μm thick ethylene-vinyl acetate (EVA) solarizing film on 17 July 2000, two weeks after CM amendment and two days after DAZ treatment, respectively. Therefore a total of 6 treatments, SOL alone or combined with DAZ or CM compost, DAZ or CM compost alone and non-treated soil, were arranged in a randomized complete block design with three replicates.

During SOL, soil temperatures at 10, 20 and 30 cm depth were monitored at 60-min intervals by T-100 probes and a CR- 10X data-logger (Campbell Scientific, Inc., USA) either in solarized and non-solarized soil.

At the end of SOL period, tomato (*Lycopersicon esculentum* Mill.) cv Naxos F_1 (having an indefinite habit) one month-old seedlings were transplanted in rows 1 m apart (3.3 plants m^{-2}) on 24 August 2000 and tomato fruits were harvested from 27 November 2000 to 26 January 2001. On 23 March 2001, melon (*Cucumis melo* L. var. *reticulatus* Naud. cv Drake F_1) was directly sown in rows 2 m apart (0.5 plants m^{-2}), after a 15 cm soil rotavation and the complete removal of tomato crop residues. Fruits were harvested from 22 June to 6 July 2001. In the following spring 'cherry' tomato cv Tomito F_1 (a dwarf plant genotype) was transplanted in rows 1 m apart, 3.3 plants m^{-2}, on 28 March 2002, whereas the fruit bunches were harvested from 17 to 27 June. During the three crop cycles soil was mulched with a black LDPE plastic film and plants received fertilizer application and irrigation according to the vegetable cultural practices of the area.

The effect of different treatments on plant growth was evaluated by recording the flowering date of each flower cluster in the first tomato crop and the plant dry weight and leaf area in the following melon crop on 5 plants from each subplot.

Number and weight of marketable fruits, average fruit weight and fruit soluble solids (°Brix) and dry matter content were assessed on the 10 tomato or 6 melon central plants in each subplot at the end of each crop cycle. Moreover, nematode infestation (root gall index) was estimated on the roots of the same plants, 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). At the same time, a composite soil sample of 40 cores was collected from 0-30 cm soil layer with a soil probe, 1.5 cm diameter and 30 cm long, in the center square meter of each plot. Eggs and juveniles were extracted from 500 cm^{-3} aliquots by Coolen (1979)'s method and counted. Moreover, after solarization treatment and at the end of each crop cycle the weeds from a 2-m^2 sampling area in the center of each plot and from the nonmulched soil between the rows were counted and classified and their dry weight was determined. Weed biomass was completely removed from the soil after each observation.

Daily temperature trend at 10, 20 and 30 cm depth, either in solarized and non solarized soil, was graphically described with reference to a representative solarization week (25 July - 31 July 2000), whereas the cumulative number of hours of temperature permanence above 40 °C was calculated for the whole solarization period. Nematode and weed data were statistically analyzed after Ln (x + 1) transformation for homogenization of error variances. All data were statistically analyzed by ANOVA, and means separated by Fisher's Least Significant Difference Test at $\alpha \leq 0.05$.

3. Results

3.1 Effects on soil temperatures

During the representative solarization week, temperatures in the first 10 cm solarized soil were always higher than in nonheated control and persisted constantly above 37 °C either during the day and over the night (Fig. 1). In solarized soil, peak temperatures at 20 cm depth were lower than in the upper 10 cm, though ranging just below 50 °C, whereas the lowest thermal values never decreased under 38 °C. Temperatures in solarized soil were still higher than 37 °C also at 30 cm depth.

Considering the whole solarization period, temperatures in solarized soil persisted in the range 40-45 °C for 301, 404 and 595 hours at 10, 20 and 30 cm depth, respectively, whereas only 173, 7 and 0 hours, respectively at 10, 20 and 30 cm depth, were totalled in the nonsolarized soil (Tab. 1). A lower cumulative number of hour was recorded in the 46-50 °C interval, as a permanence of 176, 276 and 74 hrs in solarized soil and of 48, 0 and 0 hrs in the nonsolarized soil was reached, respectively at 10, 20 and 30 cm depth. Only the upper 10 cm layer of solarized soil totalled 63 and 43 hours of permanence in the 51-55 °C and > 56 °C temperature ranges, respectively.

Table 1. Cumulative number of hours of temperature permanence above 40 °C at 10, 20 and 30 cm depth in solarized and nonsolarized soil.

Treatment	Temperature ranges											
	40-45 °C			46-50 °C			51-55 °C			≥ 56 °C		
	10 cm	20 cm	30 cm	10 cm	20 cm	30 cm	10 cm	20 cm	30 cm	10 cm	20 cm	30 cm
Solarized	301	404	595	176	276	74	163	0	0	43	0	0
Nonsolarized	173	7	0	48	0	0	0	0	0	0	0	0

3.2 Effects on crop yield

In the first tomato cycle SOL treatment resulted in a faster tomato plant growth and in a significantly earlier formation and blooming of flower clusters, particularly evident on the 3rd and 4th clusters, 12 and 16 days earlier than the unsolarized plots, respectively, whereas flowering of other clusters occurred 5-7 days before (Fig. 2). Blooming of plants in DAZ-treated soil was from 2 to 7 days earlier than control, whereas an intermediate behaviour was found in plants from CM-treated soil. SOL significantly increased marketable yield (+ 182 % as a mean) and number of fruits per plant (+ 107 %), compared to non-solarized treatments (Tab. 2). Moreover, a significantly higher weight and a lower content of dry matter and soluble solids were also found in the fruits from plants in solarized soil.

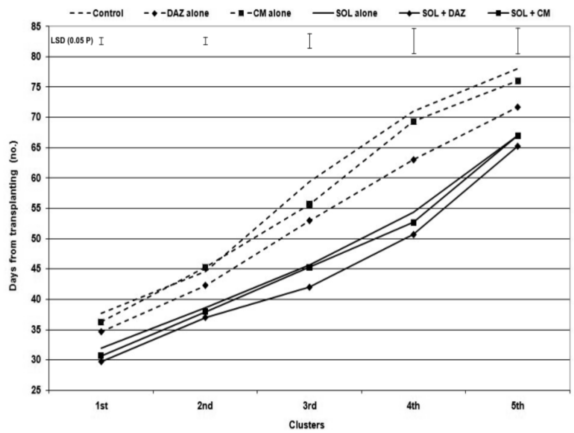

Figure 2. Effect of soil solarization (SOL), Dazomet (DAZ) or composted chicken manure (CM) either alone or in combination, on blooming time of different flower clusters in the tomato cv Naxos crop.

SOL positively affected also plant growth parameters in the following melon crop, as plant dry weight and leaf area at thinning (25 days after sowing) were significantly higher in solarized plots than in the untreated control or in DAZ or CM-treated soil (Fig. 3). Marketable fruits from SOL -treated soil were also significantly more (+ 350%), heavier (+ 461%) and with a higher dry matter and soluble solids content than in the control (Tab. 3). The effects of SOL was extended also to the yield of the third crop cycle, as tomato yield of solarized plots was increased by 76% compared to nonsolarized ones, due to a higher number (+ 49%) and weight (+ 34%) of fruits, whereas no statistical difference was found for dry matter and soluble solids content (Tab. 4).

Table 2. Effect of soil solarization (SOL), either alone or combined with dazomet (DAZ) or composted chicken manure (CM) on tomato cv Naxos yield parameters and infestation of the root-knot nematode *Meloidogyne javanica*.

Treatment	Yield parameters					*M. javanica* infestation parameters	
	Marketable yield		Fruit quality				
	(T ha^{-1})	Number of fruits per plant	Weight (g)	Dry matter (%)	Soluble solids (°Brix)	Root gall index	Eggs and J_2 ml^{-1} soil
Control	16.6 d	6.1 d	80.5 b	7.2 a	5.5 a	4.9 a	6.1 a
DAZ alone	26.0 c	8.7 c	88.7 b	6.1 b	4.9 b	4.9 a	5.4 a
CM alone	16.9 d	5.9 d	85.2 b	6.8 a	4.9 b	4.3 a	2.91 b
SOL alone	49.9 b	13.0 b	115.6 a	5.8 bc	4.3 c	0.1 b	0.6 c
SOL + DAZ	63.1 a	16.0 a	118.3 a	5.4 c	4.1 c	0.1 b	0.5 c
SOL + CM	54.7 b	13.8 b	118.4 a	5.7 bc	4.1 c	0.0 b	0.5 c

Data followed by the same letters on the same column are not significantly (P = 0.05) different according to Least Significant Difference's Test.

Table 3. Effect of soil solarization (SOL), either alone or combined with dazomet (DAZ) or composted chicken manure (CM) on melon cv Drake yield parameters and infestation of the root-knot nematode *Meloidogyne javanica*.

Treatment	Yield parameters					*M. javanica* infestation parameters	
	Marketable yield		Fruit quality				
	(T ha^{-1})	Number of fruits per plant	Weight (g)	Dry matter (%)	Soluble solids (°Brix)	Root gall index	Eggs and J_2 ml^{-1} soil
Control	10.8 b	1.5 b	1.9 a	5.4 c	8.8 c	5.0 a	5.7 a
DAZ alone	6.2 b	0.7 b	2.2 a	6.1 bc	10.1 bc	5.0 a	5.5 a
CM alone	9.1 b	1.2 b	1.9 a	5.6 bc	9.7 bc	5.0 a	3.1 b
SOL alone	50.2 a	5.4 a	1.9 a	7.9 a	12.6 a	0.9 b	0.4 c
SOL + DAZ	47.4 a	5.3 a	2.0 a	7.0 ab	11.2 ab	1.0 b	0.4 c
SOL + CM	48.7 a	5.6 a	1.8 a	8.2 a	12.2 a	0.8 b	0.3 c

Data followed by the same letters on the same column are not significantly (P = 0.05) different according to Least Significant Difference's Test.

Table 4. Effect of soil solarization (SOL), either alone or combined with dazomet (DAZ) or composted chicken manure (CM) on tomato cv Tomito yield parameters and infestation of the root-knot nematode *Meloidogyne javanica*.

Treatment	Yield parameters					*M. javanica* infestation parameters	
	Marketable yield		Fruit quality				
	(T ha^{-1})	Number of fruits per plant	Weight (g)	Dry matter (%)	Soluble solids (°Brix)	Root gall index	Eggs and J_2 ml^{-1} soil
Control	20.0 b	69.0 b	16.0 b	7.4 a	6.8 a	4.8 a	4.1 a
DAZ alone	22.8 b	72.0 b	14.9 b	7.5 a	7.0 a	4.2 a	4.0 a
CM alone	21.4 b	75.3 b	14.4 b	7.0 a	6.5 a	4.5 a	4.2 a
SOL alone	37.0 a	112.0 a	19.0 a	7.1 a	6.7 a	0.8 b	1.8 b
SOL + DAZ	38.4 a	108.0 a	18.4 a	7.3 a	6.7 a	0.5 b	1.9 b
SOL + CM	37.7 a	103.1 a	18.7 a	7.8 a	7.0 a	1.1 b	1.7 b

Data followed by the same letters on the same column are not significantly (P = 0.05) different according to Least Significant Difference's Test.

Compared to the nontreated soil, application of DAZ alone resulted in a significantly higher number of fruits and marketable yield and in

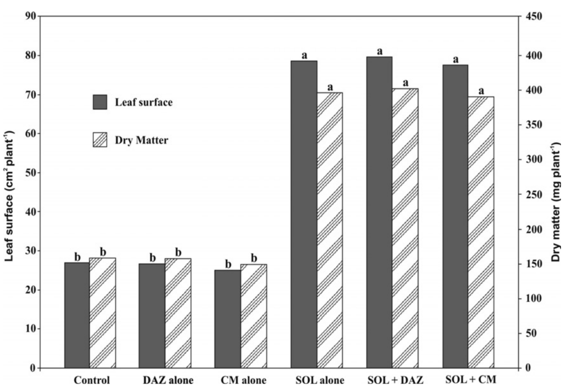

Figure 3. Effect of soil solarization (SOL), Dazomet (DAZ) or composted chicken manure (CM) either alone or in combination, on plant dry weight and leaf surface at thinning in the melon cv Drake crop.

Data of each character followed by the same letters are not significantly (P = 0.05) different according to Least Significant Difference's Test.

lower dry matter and soluble solid content only in the first crop cycle, whereas no further effect was found in the following melon and 'cherry' tomato. However, yield and fruit quality parameters of DAZ-treated soil were always significantly worse than in solarized plots. Application of CM alone significantly affected only the fruit soluble solid content in the first tomato crop, but no other effect on crop yield derived from this treatment.

No significant improvement of the effect of SOL alone on yield parameters was achieved by its combination with DAZ or CM compost.

3.3 Effects on root-knot nematodes

In the first tomato cycle and in following melon crop the heat treatment significantly reduced the soil population of *M. javanica* and the formation of root galls compared to non-treated control and DAZ or CM alone (Tabb. 2-3). No significant increase of this nematicidal effect derived from the combination of SOL with CM or

Table 5. Effect of soil solarization (SOL), either alone or combined with Dazomet (DAZ) or composted chicken manure (CM) on weed emergence at the end of soil solarization.

Treatment	Perennial species				Annual species			
	Cyperus rotundus L.		*Cynodon dactylon* (L.) Pers.		*Digitaria sanguinalis* (L.) P.B.		*Portulaca oleracea* L.	
	Number ($n\ m^{-2}$)	Dry weight ($g\ m^{-2}$)	Number ($n\ m^{-2}$)	Dry weight ($g\ m^{-2}$)	Number ($n\ m^{-2}$)	Dry weight ($g\ m^{-2}$)	Number ($n\ m^{-2}$)	Dry weight ($g\ m^{-2}$)
Control	7.3 a	13.5 a	1.0 a	2.7 a	26.0 a	17.0 a	22.3 a	57.7 a
DAZ alone	7.3 a	13.7 a	1.3 a	3.7 a	3.0 b	1.0 b	1.7 b	6.0 b
CM alone	8.0 a	15.0 a	1.0 a	2.7 a	27.3 a	20.8 a	3.0 b	10.6 b
SOL alone	0 b	0 b	0 b	0 b	0 b	0 b	0 b	0 c
SOL + DAZ	0 b	0 b	0 b	0 b	0 b	0 b	0 b	0 c
SOL + CM	0 b	0 b	0 b	0 b	0 b	0 b	0 b	0 c

Data followed by the same letters on the same column are not significantly (P = 0.05) different according to Least Significant Difference's Test.

DAZ. Soil amendment with CM did not result in any significant effect on root galling but significantly suppressed nematode population compared to control and DAZ alone. Nematode infestation was not significantly affected by the only application of DAZ. At the end of the second tomato crop nematode population density and number of root galls resulted significantly reduced only in the soil previously solarized, whereas DAZ or CM-treated plots were not different from non-treated control (Tab. 4).

3.4 Effects on weeds

At the end of solarization period, all the heat-treated plots, either with SOL alone or combined with DAZ or CM, were completely free of weeds, as high soil temperatures stopped germination or shooting of weed seeds or propagules, included the heat-resistant species (Tab. 5). Two poliennal, *Cyperus rotundus* L. and *Cynodon dactylon* (L.) Pers., and two annual, *Digitaria sanguinalis* (L.) Scop. and *Portulaca oleracea* L., weed species were found in nonsolarized soil. Compared to nontreated control, DAZ significantly reduced the number and the dry weight of both annual species, whereas CM treatment was suppressive only on *P. oleracea*. Presence of poliennal weeds was not significantly influenced by both DAZ and CM treatments.

Weed infestation was low in the autumn-winter tomato crop following SOL treatment. Heating soil, alone or combined with DAZ or CM, completely eliminated either annual *D. sanguinalis* and *P. oleracea* and perennial C. *dactylon*, whereas no effect was found on *C. rotundus* (Tab. 6). Emergence of both annual species was significantly lower in DAZ-treated soil than in CM-treated or untreated plots.

Melon crop in spring 2001 was prevalently

Table 6. Effect of soil solarization (SOL), either alone or combined with Dazomet (DAZ) or composted chicken manure (CM) on weed emergence in 'Naxos' tomato crop.

Treatment	Perennial species				Annual species			
	Cyperus rotundus L.		*Cynodon dactylon* (L.) Pers.		*Digitaria sanguinalis* (L.) P.B.		*Portulaca oleracea* L.	
	Number ($n\ m^{-2}$)	Dry weight ($g\ m^{-2}$)	Number ($n\ m^{-2}$)	Dry weight ($g\ m^{-2}$)	Number ($n\ m^{-2}$)	Dry weight ($g\ m^{-2}$)	Number ($n\ m^{-2}$)	Dry weight ($g\ m^{-2}$)
Control	1.2 a	2.3 a	2.7 a	3.5 a	3.4 a	4.3 a	3.9 a	9.6 a
DAZ alone	1.3 a	2.5 a	2.5 a	3.7 a	0.6 b	0.9 b	0.9 b	2.2 b
CM alone	1.4 a	2.6 a	2.3 a	3.4 a	3.5 a	4.0 a	3.1 a	8.7 a
SOL alone	1.0 a	2.2 a	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b
SOL + DAZ	1.5 a	2.9 a	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b
SOL + CM	1.2 a	2.4 a	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b

Data followed by the same letters on the same column are not significantly (P = 0.05) different according to Least Significant Difference's Test.

Table 7. Effect of soil solarization (SOL), either alone or combined with Dazomet (DAZ) or composted chicken manure (CM) on weed emergence in melon crop.

Treatment	Perennial species						Annual species					
	Cyperus rotundus L.		*Cynodon dactylon* (L.) Pers.		*Digitaria sanguinalis* (L.) P.B.		*Portulaca oleracea* L.		*Solanum nigrum* L.		*Melilotus sulcatus* Desf.	
	Number (n m^{-2})	Dry weight (g m^{-2})	Number (n m^{-2})	Dry weight (g m^{-2})	Number (n m^{-2})	Dry weight (g m^{-2})	Number (n m^{-2})	Dry weight (g m^{-2})	Number (n m^{-2})	Dry weight (g m^{-2})	Number (n m^{-2})	Dry weight (g m^{-2})
Control	8.2 a	18.9 a	2.7 a	17.0 a	148.7 a	372.5 a	13.3 a	54.4 a	13.3 a	126.7 a	0.0 c	0.0 c
DAZ alone	8.0 a	19.5 a	2.4 a	15.8 a	10.6 b	39.7 b	2.3 b	10.9 b	0.0 b	0.0 b	0.0 c	0.0 c
CM alone	7.7 a	18.1 a	2.4 a	14.8 a	106.6 a	273.6 a	10.7 a	47.5 a	8.0 a	73.3 a	0.0 c	0.0 c
SOL alone	7.5 a	19.1 a	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	10.7 a	84.4 a
SOL + DAZ	5.3 a	12.5 a	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	6.7 b	56.7 b
SOL + CM	8.0 a	20.1 a	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	0.0 b	8.0 b	65.1 b

Data followed by the same letters on the same column are not significantly (P = 0.05) different according to Least Significant Difference's Test.

infested by four annual species, mostly *D. sanguinalis* (Tab. 7). All the SOL treatments completely suppressed annuals *D. sanguinalis*, *P. oleracea* and *Solanum nigrum* L., and the poliennal *C. dactylon*. Density of *C. rotundus* was statistically not different in all the six treatments whereas SOL alone and, at a less extent, SOL + DAZ or CM, significantly increased the density of the annual species *Melilotus sulcatus* Desf. compared to nontreated soil. Significant reductions of plant density and dry weight were caused by DAZ alone on *D. sanguinalis*, *P. oleracea* and *S. nigrum* and by CM alone on *M. sulcatus*.

Tomato crop of spring 2002 was infested by many weeds, particularly annual species (Tab. 8). Number and dry biomass of *D. sanguinalis* and *P. oleracea* were still significantly lower in SOL-treated than in untreated soil, whereas no statistical difference was found for the emergence of annual *S. nigrum* and *M. sulcatus* and the perennial *C. rotundus* and *C. dactylon*. DAZ and CM, either alone and combined with SOL did not exert any further reduction of weed emergence.

4 Discussion

4.1 Soil temperatures

SOL treatment succeeded in raising soil temperatures at 0-30 cm depth above the lethal thresholds estimated for most soil pathogens and weeds. Ruiz et al. (2003) found LD_{95} values of 813, 281 and 32.4 min at 39, 42, and 46 °C,

Table 8. Effect of soil solarization (SOL), either alone or combined with Dazomet (DAZ) or composted chicken manure (CM) on weed emergence in spring tomato crop (cv Tomito).

Treatment	Perennial species						Annual species					
	Cyperus rotundus L.		*Cynodon dactylon* (L.) Pers.		*Digitaria sanguinalis* (L.) P.B.		*Portulaca oleracea* L.		*Solanum nigrum* L.		*Melilotus sulcatus* Desf.	
	Number (n m^{-2})	Dry weight (g m^{-2})	Number (n m^{-2})	Dry weight (g m^{-2})	Number (n m^{-2})	Dry weight (g m^{-2})	Number (n m^{-2})	Dry weight (g m^{-2})	Number (n m^{-2})	Dry weight (g m^{-2})	Number (n m^{-2})	Dry weight (g m^{-2})
Control	5.1 a	11.9 a	1.5 a	3.4 a	28.1 a	76.2 a	7.3 a	22.1 a	3.3 a	19.2 a	1.0 a	8.0 a
DAZ alone	5.0 a	12.5 a	1.5 a	3.8 a	30.1 a	81.1 a	6.9 a	25.1 b	2.0 a	16.0 a	0.7 a	6.2 a
CM alone	4.6 a	12.1 a	1.4 a	4.3 a	32.0 a	73.1 a	5.9 a	19.2 a	1.7 a	15.0 a	0.8 a	7.6 a
SOL alone	4.7 a	11.1 a	1.3 a	4.0 a	5.9 b	11.0 b	0.7 b	2.3 b	2.1 a	20.0 a	1.3 a	10.4 a
SOL + DAZ	3.9 a	12.3 a	1.6 a	3.9 a	4.3 b	9.6 b	0.3 b	1.6 b	3.0 a	27.0 a	0.9 a	9.1 a
SOL + CM	5.1 a	10.1 a	1.2 a	4.3 a	3.9 b	10.6 b	0.8 b	2.6 b	1.9 a	17.2 a	0.6 a	7.1 a

Data followed by the same letters on the same column are not significantly (P = 0.05) different according to Least Significant Difference's Test.

respectively, for the root-knot nematode *M. incognita* Kofoid *et* White Chitw. after the application of constant temperature-time dosages to infested soil. LD_{50} of seeds of 8 common weed species was found at 50 to 66 °C at 12 hours of exposure (Egley, 1990), whereas Rubin and Benjamin (1984) reported that a 30-min exposure at a 30 to 90 °C temperature range decreased the viability of *C. rotundus* L. tuber in an inverse linear manner. Number of hours of lethal temperatures depends primarily on climate conditions, but can be related also to other factors, including soil structure, color, organic matter content and seedbed preparation (Grinstein and Hetzoni, 1991).

4.2 Crop yields

Faster tomato and melon growth in solarized plots, as testified by the earlier flowering and the heavier plants, respectively, may be related to the increased nitrogen availability in heat-treated soil already reported by other authors (Chen et al., 2000; Grunzweig et al., 1999). Short-term availability of soluble forms of nitrogen, and particularly NH_4^+ and NO_3^- fractions, was usually found increased after solarization, due to the higher decomposition rates of organic matter and the mineralization of microbial biomass killed by heat (Chen and Katan, 1980; Grunzweig et al., 1999).

Positive effects of soil solarization on crop yield emerging in our experiment have been largely documented since many years (Davis, 1991; Gamiel and Katan, 1991; Stapleton and Devay, 1984) and resulted particularly evident under greenhouse conditions, where crop yield and quality was found to last for more than two crop cycles (Candido et al., 2008). 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. Stapleton and DeVay (1984) suggested that the beneficial effect of thermal treatment on crop yield can be related not only to the suppression of nematodes and weeds, but also to the release of nutrients induced by high soil temperatures. Residual effect of SOL on crop yield and fruit quality was extended to the two following crop cycles, but the long time effect of solar heating was already known from previous studies either in field (Katan et al., 1983) and particularly in greenhouse (Candido et al., 2008; Ioannou, 2000).

Yield response of DAZ was positive, though limited to the first crop cycle. The high mineralizing power of DAZ and the consequent increased nitrogen availability in DAZ-treated soil may account for the plant growth stimulation and yield increase effects of this fumigant (Scopa and Dumontet, 2007). Absence of a yield effect of CM amendment, either alone or combined with SOL, in all the three crop cycles is in contrast with previous literature, always reporting an increased crop yield as following CM soil amendments, mostly due to the CM effect on the major soil nutrients (Reddy et al., 2008) and to the suppression of soil pathogens and/or the modification of soil microbial community structure (Carrera et al., 2007; Hoitink and Boehm, 1999).

4.3 Root-knot nematodes

The SOL treatment suppressed nematode population and root gall formation along all the three crop cycles, confirming the excellent control of root-knot nematodes by SOL in greenhouse known since many years (Cartia, 1998). In more recent greenhouse experiments, the solarizing treatment drastically reduced plant infestation and root galling by *M. javanica* on tomato (Candido et al., 2008), as well as almost eradicated root-knot nematode population (Ostrec and Rubisic, 2003). In contrast to our results, the residual effectiveness of SOL was generally found to be limited by the greater soil depths inhabited by phytopathogenic nematodes and their rapid migration to upper soil layers after the treatment, as resulting in a quick recolonization of solarized soil (Stapleton and Heald, 1991).

DAZ treatment alone failed to control *M. javanica* infestation in our experiment, but previous greenhouse studies generally reported an effective control of root-knot nematode by preplant treatments with DAZ (Giannakou et al., 2002; Nagesh and Parvatha Reddy, 2005). Effectiveness of DAZ was found strictly related to optimal soil temperature, moisture and texture conditions (Fritsch and Huber, 1995): therefore failure of any of these conditions may have compromised treatment effect. Moreover DAZ, as mostly a fungicide, may have suppressed soil population of nematode antagonistic or parasitic fungi, allowing a quick soil recolonization by phytonematodes. Adversely, the population of *M. javanica* was consistently reduced by CM amendment alone along two crop cycles, confirming CM suppressivity on root-knot nematodes reported in a number of previous studies (D'Addabbo et al., 2003; Kaplan et al., 1992). Nematotoxicity of CM was generally related to the release of ammoniacal compounds (Tenuta and Lazarovits, 2002; Ben-Yephet et al., 2005), though also the effect on trophic diversity in soil nematode communities and the increase of nematode-antagonistic microbial population should be evaluated (Koenning and Barker, 2004; Riegel et al., 1996).

In this experiment no further improvement of nematicidal activity of SOL derived from the combination with a DAZ or CM treatment, but in previous greenhouse trials integration of SOL with low doses of DAZ decreased population densities of root-knot nematodes (Yucel et al., 2007). Combining SOL with CM was also previously reported to be potentially synergic and effective in reducing root-knot nematodes. Gamliel and Stapleton (1993) controlled *M. incognita* efficiently and increased lettuce yield by adding a CM compost to soil before SOL, and in more recent greenhouse trials SOL and CM were more effective when combined than alone in reducing the soil population of root-knot nematodes and gall formation on tomato and pepper plants (Kafikavalci, 2007; Oka et al., 2007).

Moreover, in a field experiments over two cropping seasons a 7-week SOL combined with 10 T ha^{-1} CM, provided also an effective control of most annual weed species (Benlioğlu et al., 2005). Gamliel et al. (1999) reported that the high temperatures raised by SOL increase the generation of toxic compounds by CM, enhancing toxic activity against soil borne pathogens, nematodes and weeds. Oka et al. (2007) suggested that the plastic film would entrap higher concentrations of ammonia in the soil for longer periods, thus enabling a more effective diffusion in the soil. Finally, the combination of SOL with a CM amendment may also improve the chemical fertility and impact positively the microbiological parameters of soil, as organic matter exerts a protective role on soil microbial biomass and enzymatic activities against the detrimental effect of heating (Clark et al., 2007; Scopa and Dumontet, 2007).

4.4 Weeds

SOL treatment completely suppressed the emergence of all the annual and perennial weed species, though *C. rotundus* was controlled only immediately after the treatment and recovered fastly in the following crop cycles. SOL effects on weed population were hypothesized to be due to different mechanisms, as changes in cell metabolism and ultrastructure (Singla et al., 1997), microbial parasitism on seeds weakened by sublethal temperatures, seed dormancy interruption by raising temperatures, foliar scorching of weeds under the plastic mulch (Egley, 1990).

A satisfactory SOL control of annual weeds was reported also in the previous studies. Stapleton et al. (2005) found that solar heating reduced by nearly 100% a wide range of annual weeds, including *Melilotus* spp and *Digitaria* spp., and Candido et al. (2008) reported that the emergence of many annual species, among which also *D. sanguinalis* and *S. nigrum*, was almost completely suppressed by greenhouse SOL. In a weed classification based on heat sensitivity, *P. oleracea*, was reported as undefined behaviour species (Restuccia et al., 1994), though Dahlquist et al. (2007) found a 39 °C temperature sublethal to seeds of *P. oleracea*, and infestation of this species was drastically reduced by a field SOL treatment (Patricio et al., 2006). Most perennial weeds were generally indicated as more difficult to control than annual species, maybe due to the occurrence of propagules at soil depths not exposed to lethal temperature (Rubin and Benjamin, 1984). Failure of SOL for the control of *Cyperus* spp. was reported by many studies (Candido et al., 2008; Stapleton et al., 2005), though a number of reports documented also an effective control of *Cyperus* spp and other perennial weeds by combining the SOL treatment with low rates of herbicides (Gilreath et al., 2005), or extending the length of SOL period (Chase et al., 1998). In the above cited classification of Restuccia et al.

(1994), *C. dactylon* was ranked as an undefined behaviour species, though Rubin and Benjamin (1984) had reported the heat-sensitivity of this perennial weed.

Suppressivity of SOL on annual weeds and the perennial *C. dactylon* extended throughout the tomato and melon crop following the treatment, but the effects on *D. sanguinalis* and *P. oleracea* persisted, though at a lower size, also in the third crop. The residual effect of SOL treatment on weeds was reported by literature as much more pronounced than on nematodes and most fungal pathogens, as Candido et al. (2008) reported a consistent reduction or a total suppression of annual species and some perennial species after greenhouse SOL throughout the two following years and also later for *C. dactylon*. In other trials, soil was weed-free for at least three years after SOL in an olive orchard (Lopez-Escudero and Blanco-Lopez, 2001), and residual effects of SOL were observed on *Cyperus* spp. during four consecutive cropping seasons in a tomato-cucumber rotation (Gilreath et al., 2005). Moreover, Bell and Elmore (1983) found that persistence of weed control may be prolonged by the absence of soil disturbances after SOL treatment.

Combination of SOL with DAZ or CM did not enhance the suppressive effect on weeds. Integration with low rates of fumigants was previously found to improve SOL suppressiveness on weeds (Peachey et al., 2001), but the sequence of treatments was shown to play an important role in the final result (Eshel et al., 2000). Moreover, field and greenhouse trials demonstrated also a synergism of SOL with CM for weed control (Benlioglu et al., 2005; Haidar and Sidahmed, 2000).

DAZ treatment exerted a satisfactory control of annual weeds in the first two crop cycles, but was not effective on poliennal species, confirming the mixed results emerged from previous experiments (Landschoot et al., 2004; Locascio et al., 1997). Adversely to the previous findings (Benlioglu et al., 2005), no effective weed control was provided by CM treatment alone.

5. Conclusions

In conclusion this study showed that, in the climatic conditions of Southern Italy, greenhouse SOL alone may provide an effective suppression of root-knot nematodes and weeds, with no strict need for combination with other control tools, as chemicals or organic amendments. Moreover, SOL confirmed its positive long-term effects in vegetable crop systems. In our study, marketable yield increases were clearly evident up to two years from the heating soil treatment.

However, the integration of solar heating with other techniques could be needed in less favourable climates and in field conditions to enhance heat effects and to shorten the solarization period without reducing its efficacy.

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